

Evaluation and Demonstration of Low NOx
Burner Systems for TEOR Steam Generators
Test Report: Preliminary Evaluation of
Commercial Prototype Burner

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16. ABSTRACT The report documents preliminary testing of a 16 MW low-NOx burner for retrofit application to thermally enhanced, oil recovery steam generators. The burner is designed to achieve NOx emissions below 85 ppm (at 3 percent O2) while burning heavy fuel oil containing more than 0.6 weight percent bound nitrogen. The design of this burner (documented in a companion report) is based on optimizing conditions of stoichiometry, temperature, and residence in a separate, regeneratively cooled prechamber. Preliminary evaluations were conducted in an experimental test furnace burning a 0.74 percent nitrogen residual oil. Under optimum conditions, NOx emissions were limited to 45 ppm; CO emissions were held to 35 ppm; and the recorded Bacharach smoke number was between 2 and 4. This preliminary evaluation demonstrated the ability of the burner to produce very low NOx levels on a high nitrogen residual oil, with low smoke and CO emissions, and with a flame which appears to be compatible with steam generators. Final optimization and detailed evaluation of the burner hardware and control system will take place during the field evaluation phase of this program.		
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FOREWORD

Enhanced oil recovery processes are applied to oil field production in order to extract heavy, viscous crude oil and tar sands which cannot otherwise be produced. A significant fraction of total U.S. oil reserves require application of enhanced oil recovery in order to be realized. Thermally enhanced oil recovery (TEOR) involves injection of wet steam which is produced by combusting crude oil in oil field steam generators typically ranging in size from 7 to 15 MW capacity. More than 90 percent of all oil field steam generators in the United States are located in California, one-third (approximately 1000 units) of which are located in Kern County. Approximately one-third of the produced crude oil is consumed by the steam generator, amounting to over 200,000 barrels of crude oil consumed per day at full capacity. The crude oils which are fired in these steam generators are typically high in nitrogen (~0.8 to 1.0 percent) and sulfur content. Uncontrolled emissions of NO_x and SO_x can therefore reach high levels and potentially worsen ambient air quality.

Local legislation regulating emissions of NO_x from oil field steam generators threatens to limit oil production unless NO_x control methods are applied. A ceiling on total NO_x emissions from all steam generators in Kern County has been established which limits total emissions to 1979 levels; thus new generators cannot be brought on line without reducing emissions from existing ones. New generators are required to have "best available control technology (BACT)" which may include low- NO_x burners, postflame NH_3 injection, or other postflame treatment methods. In addition, if ambient NO_2 level in Bakersfield exceeds a specified level, the total NO_x ceiling is lowered to the equivalent of 0.14 lb NO_x /MMBtu (60 mg/MJ) or 105 ppm NO , corrected to 3 percent oxygen if all steamers were in operation. Enhanced oil recovery operations are projected to expand through 1995. The level of NO_x control required to meet both growth and air quality goals has typically been difficult to achieve with available technology while maintaining acceptable carbon monoxide and particulate emissions and practical flame conditions within the steamer.

This program addresses the need for advanced NO_x control technology for oil-field steam generators, and concerns the development of a full-scale burner system, for which the concept is based on fundamental studies. The

burner will be retrofittable to existing steam generators and will produce acceptable emissions of CO and particulate while maintaining a flame form compatible with the steamer design. The emission goals for NO_x are to achieve less than 85 ppm NO_x at 3 percent excess oxygen.

The major elements of this program are:

1. Conceptual design development--to verify and refine design scaling criteria developed under previous EPA contracts in order to develop hardware designs.
2. Detailed burner design and construction--to produce a commercial-grade full-scale burner suitable for retrofit on an existing steam generator.
3. Burner optimization and evaluation--to minimize pollutant emissions in a field-operating TEOR steam generator firing high-nitrogen crude oil and evaluate performance over an extended period of time.

This report is the second of three project reports. The first two elements of the program are discussed in an interim report (February, 1983). This current report documents the initial series of full-scale burning tests conducted in EER's Medium Tunnel test furnace. The final phases of the program--field retrofit and testing--are currently in progress and will be covered in the final report.

ABSTRACT

This report describes the preliminary testing of a 16 MW low- NO_x burner for thermally-enhanced oil recovery steam generators. These "steamers" are often required to burn low grade fuels with minimum environmental impact.

The 16 MW commercial prototype burner described in this report was developed from scaling criteria generated in bench- and pilot-scale experiments. NO_x emissions can be reduced by staging the combustion process. The design of this burner is based on optimizing conditions of stoichiometry, temperature, residence time, and mixing so that NO_x emissions are minimized. The current design utilizes a separate, regeneratively-cooled prechamber. Fuel and a portion of the combustion air enter the prechamber and burn under optimum fuel-rich conditions. Secondary air is injected at the prechamber exit into the furnace where combustion is completed.

The tests were conducted in an experimental test furnace which closely simulates the thermal environment of a watertube boiler. Firing a 0.74 percent nitrogen residual fuel oil with the optimum burner configuration produced 49 ppm of NO_x , 35 ppm of CO (corrected to 3 percent oxygen) and a Bacharach smoke number of 2 to 4. Flame conditions within the furnace were favorable, with no impingement on any of the test furnace surfaces. Although the geometry of the test furnace ($L/D = 1.4$) is different from TEOR steamers ($L/D = 4$) the flame characteristics appeared to be well suited for the intended applications.

The report describes the results of tests to determine the effects of first stage parameters (swirl, throat geometry, stoichiometry) and second stage parameters (air injection geometry, excess air) on emissions and flame characteristics. Turndown was also investigated. Thermomechanical performance of the burner hardware and control system performance are also discussed.

The results of the preliminary evaluation demonstrated the ability of the burner to produce very low NO_x levels on a high nitrogen heavy residual oil, with low smoke and CO emissions and with a flame which appears to be compatible with field steam generators. The burner hardware has performed without serious mishap for the short duration of these tests. Final optimization and detailed evaluation of the burner hardware and control system will take place during the field evaluation.

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1.0 SUMMARY

Nitrogen oxide emissions from stationary combustors can be reduced by combustion modification techniques which involve staging the heat release process. Optimization of these techniques to control NO_x emissions from oil-fired combustors has proven difficult because of limited understanding of the controlling phenomena and problems associated with scaling of combustion systems. This report describes the testing of a 16 MW low- NO_x , oil-fired burner designed for application to steam generators for thermally-enhanced oil recovery (TEOR). The burner design was scaled up on the basis of criteria developed in pilot-scale combustors. The pilot-scale development was spurred by fundamental information generated in bench-scale reactors. The 16 MW commercial prototype burner developed and tested under the current program will be fully evaluated in an actual field-operating TEOR steam generator located in Kern County, California, by the end of 1983.

The objectives of these tests were to:

- Cure the refractory under controlled conditions.
- Evaluate control system operation/response and establish input/output factors.
- Establish the impact of burner settings on emissions and flame shape.
- Evaluate overall mechanical and thermal performance.

These preliminary tests were conducted in an experimental test furnace (EER's Medium Tunnel), designed to simulate the thermal environment of a watertube boiler, so that risk to field equipment would be minimized.

The design of the commercial prototype burner, discussed in detail in the referenced report by England, et al, (1983) is based on an optimized two-stage combustion system. The burner concept, illustrated in Figure 1-1, utilizes a physically separate primary combustion zone which operates with approximately 60 percent of theoretical combustion air. The first stage chamber is constructed of high temperature refractory supported within a hollow stainless steel shell. The primary combustion air is preheated as it passes through the hollow shell, simultaneously cooling the shells. This "regener-

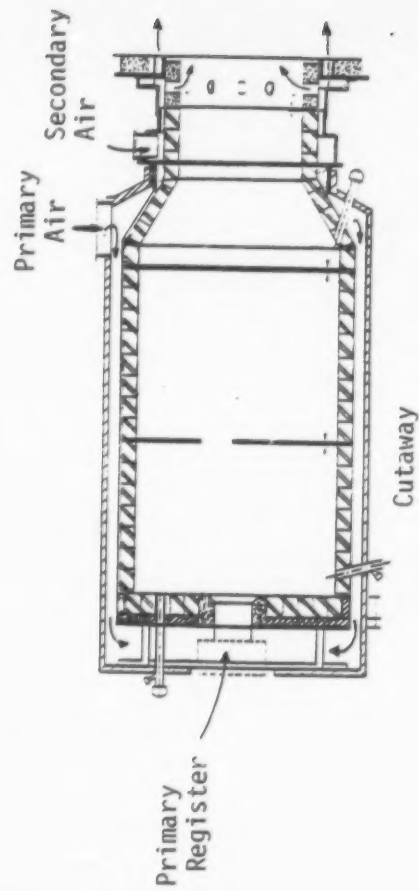
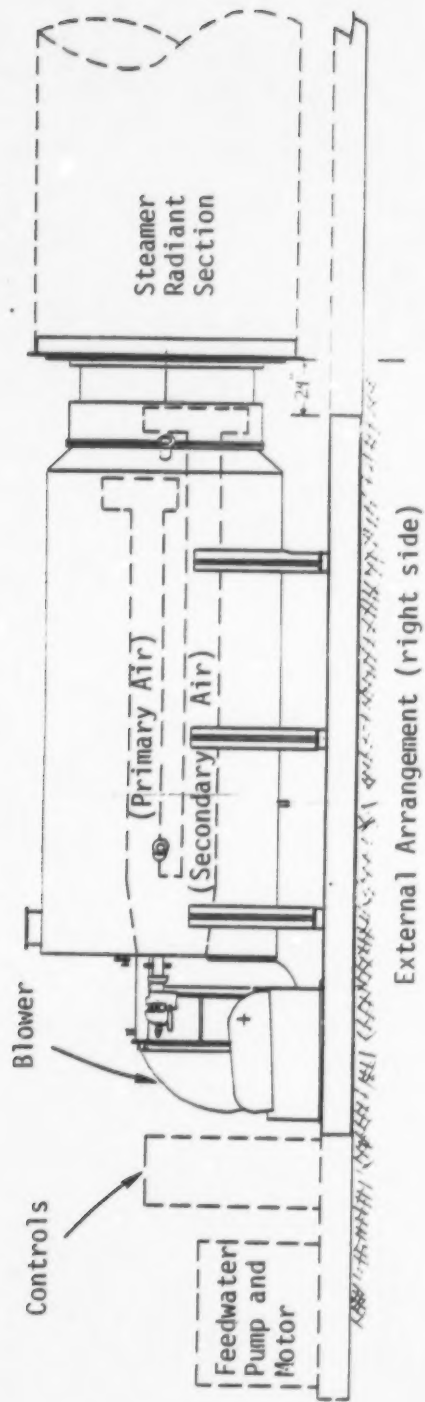


Figure 1-1. TEOR steamer low NO_x burner-regeneratively-cooled concept.

ative" concept permits the refractory lining to be thinner, minimizing heatup and cooldown time, while increasing the temperatures in the fuel vaporization zone. Fuel and the preheated primary air are injected into the first stage and burn under optimally fuel-rich conditions. This maximizes the conversion of fuel nitrogen to N_2 . The gas temperature in the first stage is maintained as high as possible in order to maximize the rate of reduced nitrogen species decay to N_2 , which makes the most efficient use of available residence time within the first stage chamber. The primary combustion products leave the first stage chamber and mix with secondary air to complete combustion within the furnace. Second stage mixing is controlled to minimize conversion of reduced nitrogen species to NO and to minimize thermal NO formation, while producing an acceptable flame shape.

The operation of the burner is supervised by a hybrid pneumatic-electronic control system. Conventional relay logic and pneumatic control signal processing are integrated with a programmable controller and instrumentation subsystem. The system is designed to provide parallel pneumatic positioning of fuel and air valves with a closed-loop metering trim control which maintains the burner at optimum conditions for NO_x , smoke, and CO emissions. The system was designed to interface easily with the existing host field steam generator.

The optimum emissions performance of the commercial prototype burner is shown in Figure 1-2. These data were obtained from a residual fuel oil, derived from California crude oil, containing 0.74 percent fuel nitrogen. Minimum NO_x emissions were 49 ppm, corrected to 3 percent oxygen, and were obtained at a first-stage stoichiometric ratio (SR_1) of 0.60. Overall excess oxygen was 3 percent for these data. CO emissions were 35 ppm and Bacharach smoke number ranged from 2 to 4. Smoke and CO were generally insensitive to SR_1 near the minimum NO_x condition.

Several burner configurations were tested to determine the optimum settings for emissions and second stage flame characteristics. The tests included variation of both first-stage and second-stage parameters. First-stage input parameters which were varied included stoichiometry, air register setting (swirl), oil gun setback, atomizer spray angle, and stabilizer. Second-stage input parameters included excess air, secondary air distribution through the radial and axial ports, and number of secondary air ports. First-

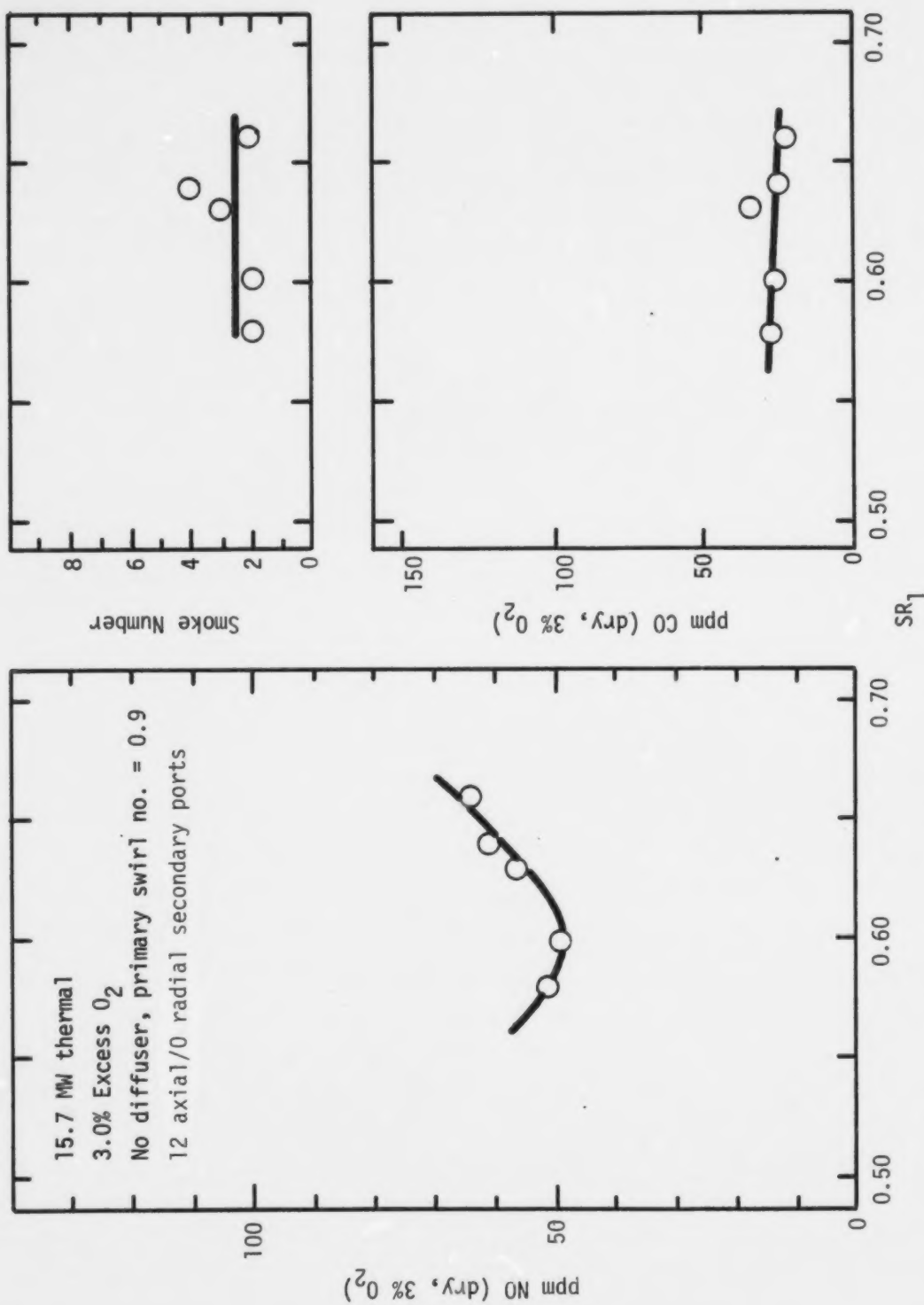


Figure 1-2. Optimum full-load emissions performance of the commercial prototype burner (medium tunnel test furnace).

stage parameters which significantly affected NO_x emissions were stoichiometry and stabilizer geometry. NO_x emissions reached a minimum as SR_1 was decreased. The bench and pilot scale development had shown that this is due to a minimum in fixed nitrogen species in the first stage. Figure 1-3 shows the effect of stabilizer geometry on NO_x emissions at full load. Two configurations were tested, which were with and without a conical diffuser at the tip of the oil gun. NO_x emissions were lower without the diffuser. This is most likely because of an improvement in the mixing characteristics in the first stage without the diffuser. Pilot-scale results had indicated that when the primary air had too little swirl first stage mixing was poor, resulting in large external recirculation zones which produce backmixing and poor residence time distribution. Backmixing is undesirable since it produces a less favorable distribution of radical species in the early part of the first stage flame - stirring is also undesirable because a broader distribution of residence times are produced. Both effects can result in increased NO_x emissions.

Smoke and CO emissions were also much lower without the diffuser. Other test results suggest that this was due to the difference in primary swirl level between the two configurations, which affected second stage flame length. High smoke and CO emissions were generally associated with a portion of the second stage flame extending into the exhaust duct of the test furnace. The test furnace is much shorter than the TEOR steamer (see dashed lines in Figure 1-4), so this condition is not likely to occur in an actual TEOR steamer.

Second stage air injection geometry was found to affect both emissions and flame shape. Secondary air was selectively injected through sets of axial or radial injection ports. Radial air injection produced high NO_x emissions. As secondary air was shifted from the radial ports to the axial ports, NO_x emissions decreased sharply; however, smoke and CO emissions increased. The high smoke and CO emissions were associated with the long flame produced with the primary diffuser in place. Variation of the number of axial ports (hence velocity) without radial air injection showed that moderate variation of flame length is possible without strongly affecting emissions. Figure 1-4 compares flame shape for 12 and 16 axial ports, corresponding to secondary air injection velocities of 50 and 35 m/s, respectively, at the minimum NO condition. A decrease in flame length of approximately 1 meter was observed for 12 ports, while minimum NO_x emissions decreased

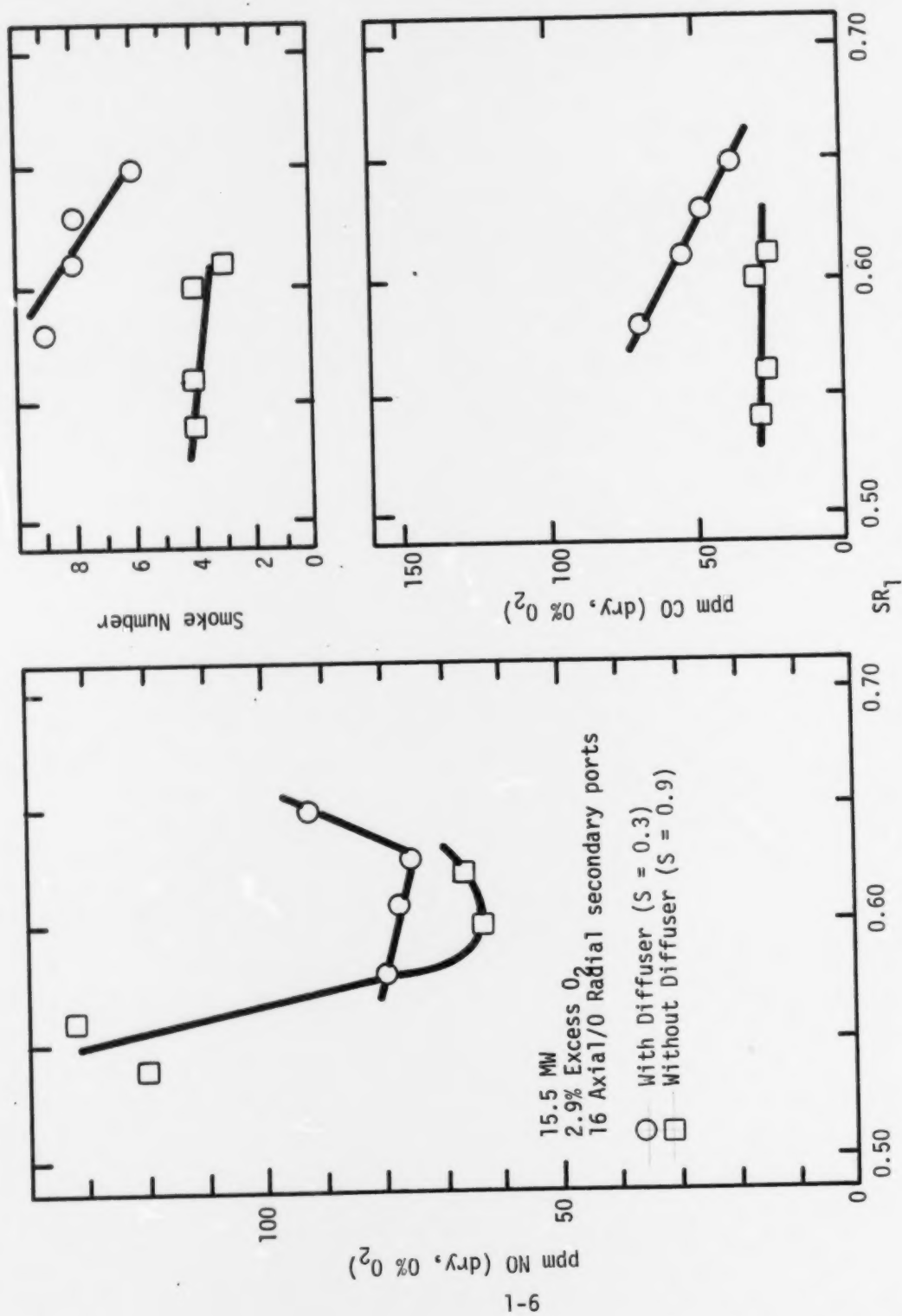


Figure 1-3. Effect of primary configuration on emissions.

16 MW

2.0 - 3.0% O_2

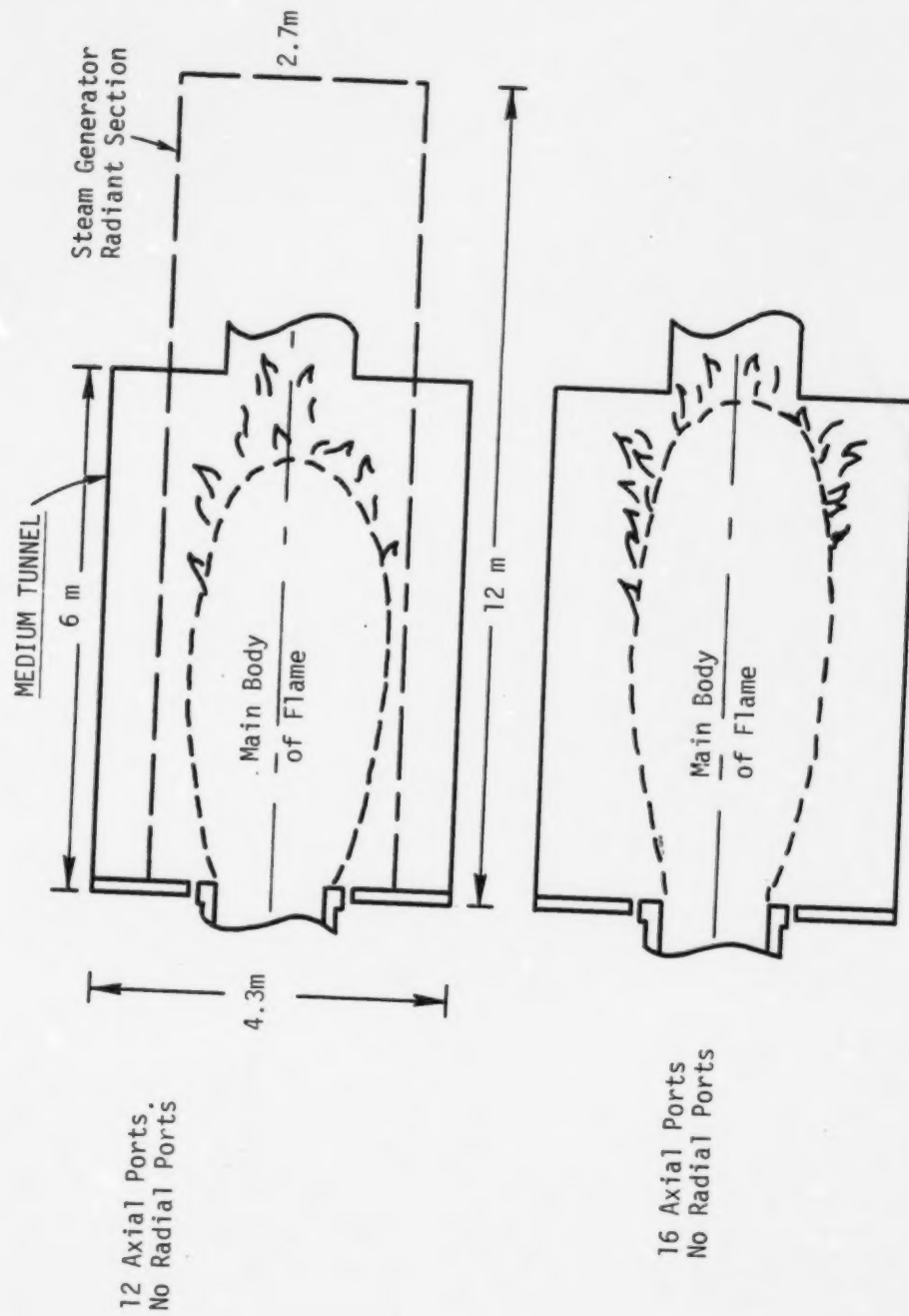


Figure 1-4. Comparison of flame length observed in the MT for the 12 and 16 axial ports (16 MW, 2.0 - 3.0% O_2).

slightly from 54 ppm to 48 ppm, corrected to 3 percent O_2 . Based on these results, final optimization of second stage mixing with respect to flame shape should be possible in the field without compromising emissions performance.

Excess oxygen in the second stage was also varied under one test condition, and results showed that NO_x emissions were relatively insensitive to O_2 level.

Hardware performance was generally excellent with the exception of minor shakedown problems. Inspection of the refractory lining after the test revealed no signs of significant damage. A portion of the lining appears to have shifted slightly due to thermal expansion; however, this is not considered serious. Overall appearance of the lining was excellent.

Thermal performance of the first-stage chamber was well within the calculated design performance. Temperature of the stainless steel shells was well below the design point maximum at normal full-load conditions. Transient thermal performance of the lining during a long term sudden shutdown was not determined.

Control system operation during light off and shutdown sequences was satisfactory. Full control system characterization was not achieved; however, a brief test of the programmable controller trim loop showed that SR_1 and excess O_2 could be closely maintained over a narrow range of load near full load. Final set up and optimization will take place in the field.

The results of the preliminary evaluation are encouraging and suggest that the program emission goals will be easily achieved in the field. Characteristics of the flame produced by the commercial prototype burner in the medium tunnel furnace are very good and should easily fit within the confines of the field steam generator radiant section.

2.0 COMMERCIAL PROTOTYPE DESIGN

The design of the 16 MW commercial (CP) burner is described in detail in the referenced report by England, et al (1983). The design highlights and the burner configurations tested will be reviewed briefly in this section.

The design of the CP burner evolved from bench-scale and pilot-scale development work which was guided by fundamental modeling of NO_x formation kinetics. This work is discussed in the referenced report by England, et al (1981) and Pershing, et al (1981). A detailed engineering study was conducted to produce the final design of the commercial prototype burner.

The burner design is based on the concept of classical two-stage combustion with a fuel-rich primary zone followed by a second-stage or burnout zone. The conceptual design criteria developed from the previous studies are given in Table 2-1. The objective of the first-stage criteria is to provide conditions of high temperature and optimum stoichiometry which maximize decay of reduced nitrogen species (primarily HCN and NH_3), evolved from the fuel-bound nitrogen, to N_2 in the available first-stage residence time. The residence time under plug-flow conditions was then selected based on pilot-scale results to achieve the program goal for NO_x emissions, i.e., below 100 ppm @ 0% O_2 (85 ppm @ 3% O_2). The objective of the second-stage criteria is to minimize both conversation of reduced nitrogen species in the first-stage products to NO and formation of "thermal" NO_x from molecular N_2 in the second-stage flame.

2.1 First-stage Chamber Design

The pilot-scale prototype burner designs utilized a heavily insulated refractory chamber for the first-stage chamber. This concept was explored for the full-scale prototype; however, based on experience with the prototype construction and detailed analysis of a full-scale insulated design, the concept was judged to be unsuitable. The thick refractory lining required to minimize heat loss results in high internal stresses during thermal transients, which would be very likely to cause partial or complete failure of the lining. These stresses can be reduced by heating and cooling the lining very slowly; however, the required rate of temperature change is impractical for conventional field generators, precluding retrofit application.

TABLE 2-1. CONCEPTUAL DESIGN CRITERIA

First Stage	<u>IGNITION ZONE</u> Dropsize Air Temperature Mixing Residence Time	Mean Dropsize <50 μm Maximum Preheat Premixed Minimum (<0.01 sec)
	<u>FUEL-RICH ZONE</u> Residence Time Bulk Temperature Stoichiometry Mixing	0.5 to 0.7 sec above 1427°C (2600°F) Rich Optimum (0.55 to 0.7) Plug Flow
Second Stage	Peak Temperature Mixing Stoichiometry	below 1538°C (2800°F) Slow to Moderate Minimum Excess Air

A regeneratively-cooled first-stage chamber design was selected for the full-scale burner which reduces the risk of refractory failure. The term "regenerative" is used in the sense that first-stage air is preheated as it passes through a refractory-lined hollow shell which forms the first stage. The use of the primary air as a cooling medium permits the refractory lining to be much thinner than the insulated concept; additionally, the primary air preheat serves to increase the rate of vaporization of the fuel droplets in the ignition zone thereby increasing the time available for gas-phase reactions to occur.

Figure 2-1 illustrates the overall arrangement of this concept. Two concentric stainless steel shells form a narrow annular passage through which the primary air flows. The inner shell is lined with high-alumina refractory brick which is 15 cm (6 inches) thick. The lining was installed with axial and radial expansion allowances to prevent high compressive stresses from occurring. Ambient temperature air enters the double shell near the exit of the first stage and convectively cools the steelwork. The preheated air then passes into the chamber through the primary register assembly. The outer shell is insulated with a ceramic fiber blanket to reduce net heat loss to the surroundings.

The exit of the first-stage chamber is reduced in diameter to serve two functions: to prevent backflow of gasses from the second-stage and to reduce radiative heat transfer from the first stage. Conical geometry was chosen to minimize recirculation zones. Diameter was chosen to provide similar exit velocity to the optimum pilot-scale configuration (15 m/sec).

2.2 Primary Air Configuration

The overall geometry of the primary throat is shown in Figure 2-2. The geometry of the primary throat and flow characteristics of the air register determine the overall flow pattern and flame stability characteristics in the first stage. Pilot-scale testing demonstrated that a relatively high primary air velocity (25-30 m/sec) and moderate degree of swirl (swirl number ~ 0.4) produced the best overall emissions performance. A commercial air register capable of generating the required level of swirl was chosen and matched to the correct throat size for the desired velocity. Swirl numbers have been calculated for the air register using the relationship given by Beer and

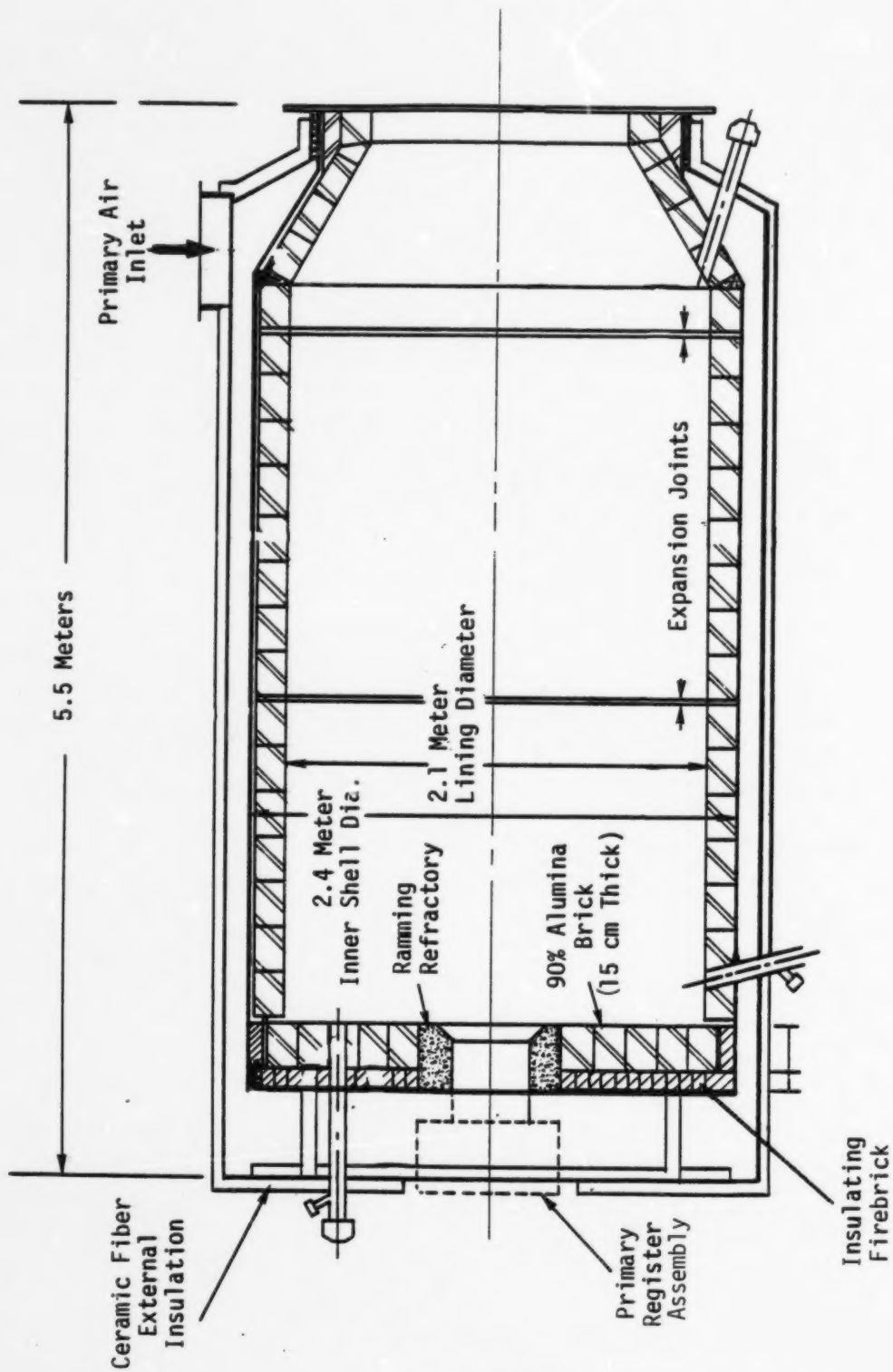


Figure 2-1. Regenerative first-stage design.

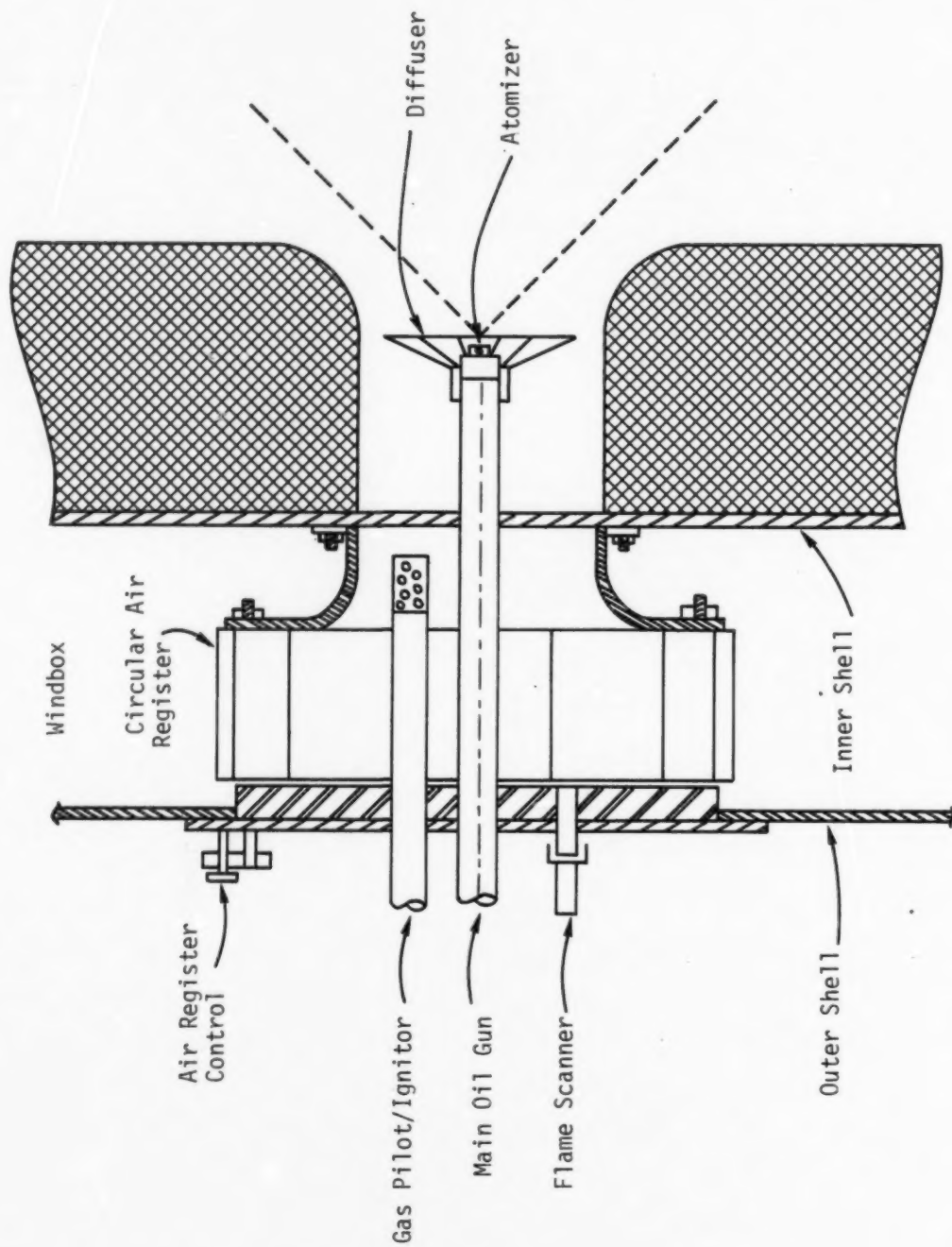


Figure 2-2. Primary throat configuration.

Chigier (1972) for radial guide vane swirl generators. Commercial oil gun atomizer, pilot/ignitor, and flame scanner components were chosen. A conical diffuser with air openings was located on the end of the oil gun to provide flame stabilization. The burner was tested with and without the diffuser.

The atomizer is an internal-mixing, twin-fluid atomizer which is designed to use steam as the atomizing fluid. Several steam and air jets impinge at the entrance to a small mixing chamber in the tip of the atomizer. The steam/oil emulsion leaves the mixing chamber through eight holes, which are drilled to produce a conical spray pattern. The nozzle used for most of the testing produced an included spray angle of 90° . The atomizer was also tested with air as the atomizing fluid, as air atomization is commonly used in the field when a steam generator is initially started up.

2.3 Secondary Air Configuration

The main features of the secondary air injection section are illustrated in Figure 2-3. A double shell arrangement similar to that used for the first-stage combustion chamber is used here also. Secondary air enters the double shell from a separate air supply and is injected into the furnace through either radial or axial ports. The distribution of air between the ports can be adjusted to control second-stage mixing and flame shape. Eight radial ports with individual dampers are located just upstream of the exit of the first stage. Sixteen ports oriented parallel to the burner axis are located in the front wall of the burner and inject air directly into the furnace. The size of the ports was selected for an air injection velocity of 15 to 20 m/s with a 50/50 split between axial and radial air. A sample port was built into the second-stage air section to permit sampling and temperature measurement of the first-stage combustion products.

2.4 Burner Controls

The burner control system was designed to provide start-up/shut-down operation compatible with normal steam generator operating sequences as well as automatic control over first-stage stoichiometry and overall excess oxygen. Additionally, the system was configured to interface simply and directly with the host steam generator selected for the field test portion of the program. The primary elements of the control system (Figure 2-4) are a programmable controller, electronic instrumentation package, pneumatic operators, relay logic package, and commercial flame safety equipment. This hybrid approach

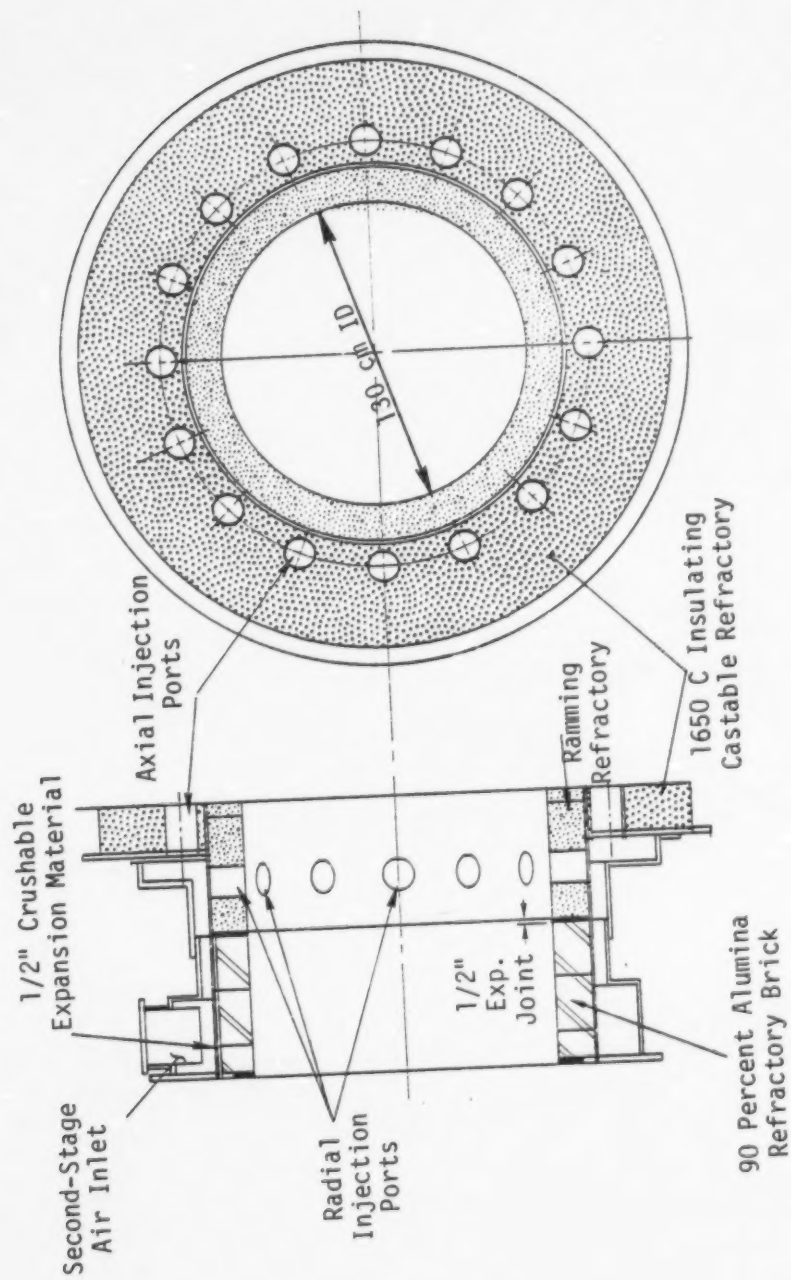


Figure 2-3. Variable second-stage air addition section.

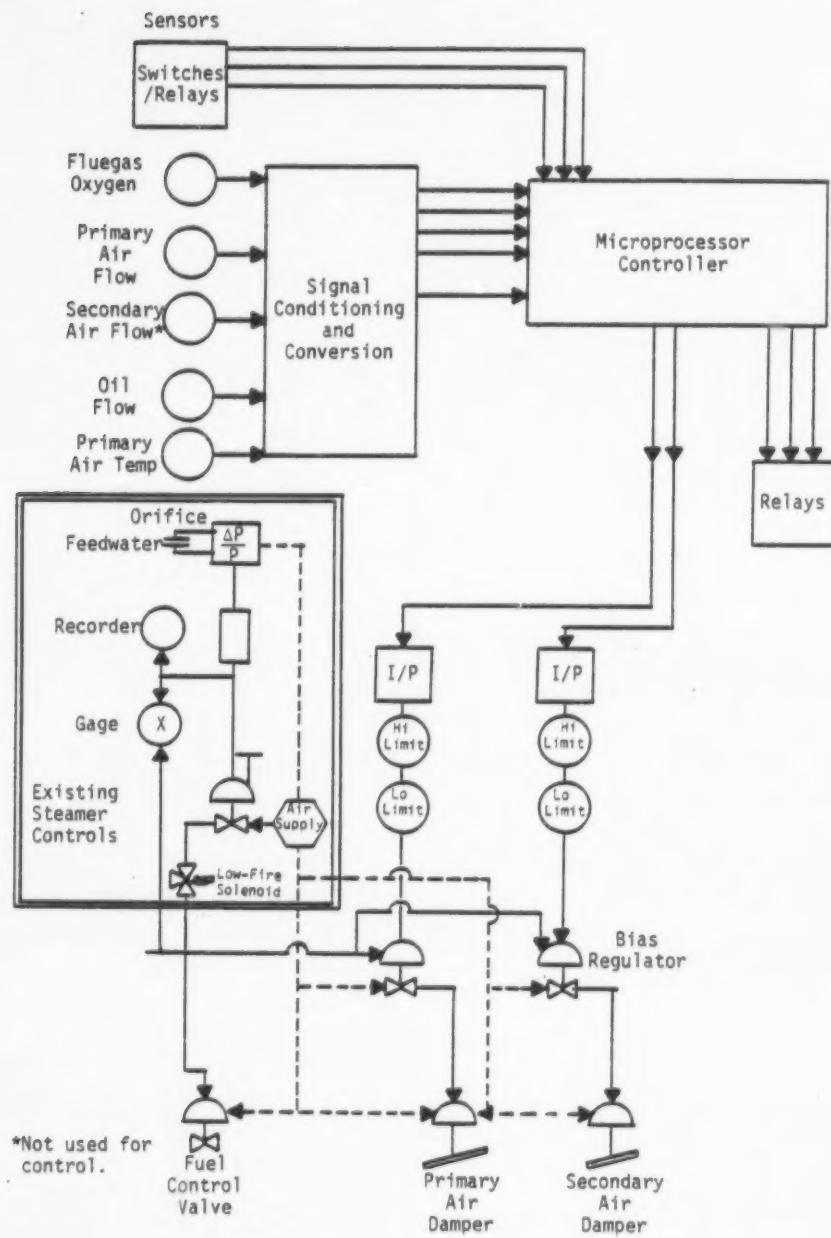


Figure 2-4. Burner control schematic.

utilizing both electronic and pneumatic components was chosen to minimize the impact of electronic component failure and to simplify interfacing in the field. The system has provision for normal flame failure and burner light-off sequences, and also initiates an emergency shut-down and shell cooling sequence in the event of excessive shell temperatures.

The overall approach utilizes a closed-loop, parallel positioning system. After the steam generator is started up, a pneumatic signal based on feedwater flow sets the position of the fuel valve. The same signal is split to position the primary and secondary air dampers. The instrumentation package measures fuel flow, air flow and stack oxygen. When the steam generator approaches full load, the programmable controller begins to trim the primary and secondary air pneumatic control signal to maintain a preset first-stage stoichiometric ratio and excess oxygen level. The maximum bias to the feedwater flow signal is limited in the event that one of the control elements fails. While controlling the burner operation to maintain minimum NO_x emissions, this approach still maintains the safety elements of the original steamer control system (in that the steam generator is protected against overheating).

3.0 MEDIUM TUNNEL TEST FACILITY

The EER Medium Tunnel (MT) test furnace (Figure 3-1) is designed for firing from 8.8 to 23.4 MW (30×10^6 to 80×10^6 Btu/hr) thermal input on gas, oil, or coal. The furnace consists of a horizontal cylinder which is externally cooled by water sprays. Part of the internal surface (approximately 60 percent) is lined with refractory to approximately simulate the thermal environment of a watertube boiler. The burner is mounted on one end of the cylinder and combustion products are exhausted on the opposite end.

The facility is equipped with a separate air supply which can be pre-heated and distributed to several separately controlled and metered locations. Since the Commercial Prototype (CP) burner incorporates its own air supply the facility air system was not utilized for these tests.

The facility has equipment for firing and metering coal, oil, or natural gas. The facility oil system is shown in Figure 3-2. Heavy fuel oil (e.g., residual, crude) or distillate fuel oil can be fired. Heavy oil is pumped from a steam-heated underground tank through heat-traced lines to the furnace area. The oil flow is metered with a mass flow meter and then passes to a steam-heat exchanger for final temperature control prior to reaching the burner. The lines can be flushed with compressed air or No. 2 oil. No. 2 oil is pumped from a separate underground tank and metered through a rotameter before reaching the burner.

The furnace exhaust passes through a long exhaust duct to a scrubbing tower for particulate control. A sampling station is located near the exhaust duct upstream of the scrubbing tower. Exhaust samples are withdrawn from the stack using a water-cooled stainless steel probe, dried in an ice-bath condenser and pumped to the control room and analyzer equipment. Table 3-1 lists the analyzers used for measurement of O_2 , CO, CO_2 and NO_x . SO_2 is sampled and measured separately using an air-cooled phase discrimination probe, heated sample lines and filter, and a Dupont NDUV analyzer. Smoke number was manually determined using a Bacharach Smoke Spot pump. First-stage exit temperature and MT exit temperature were measured using suction pyrometers. The analyzer outputs are recorded on strip recorder and, together with other metering and furnace instrumentation, collected on a datalogger/computer system which provides on-line data reduction and printout.

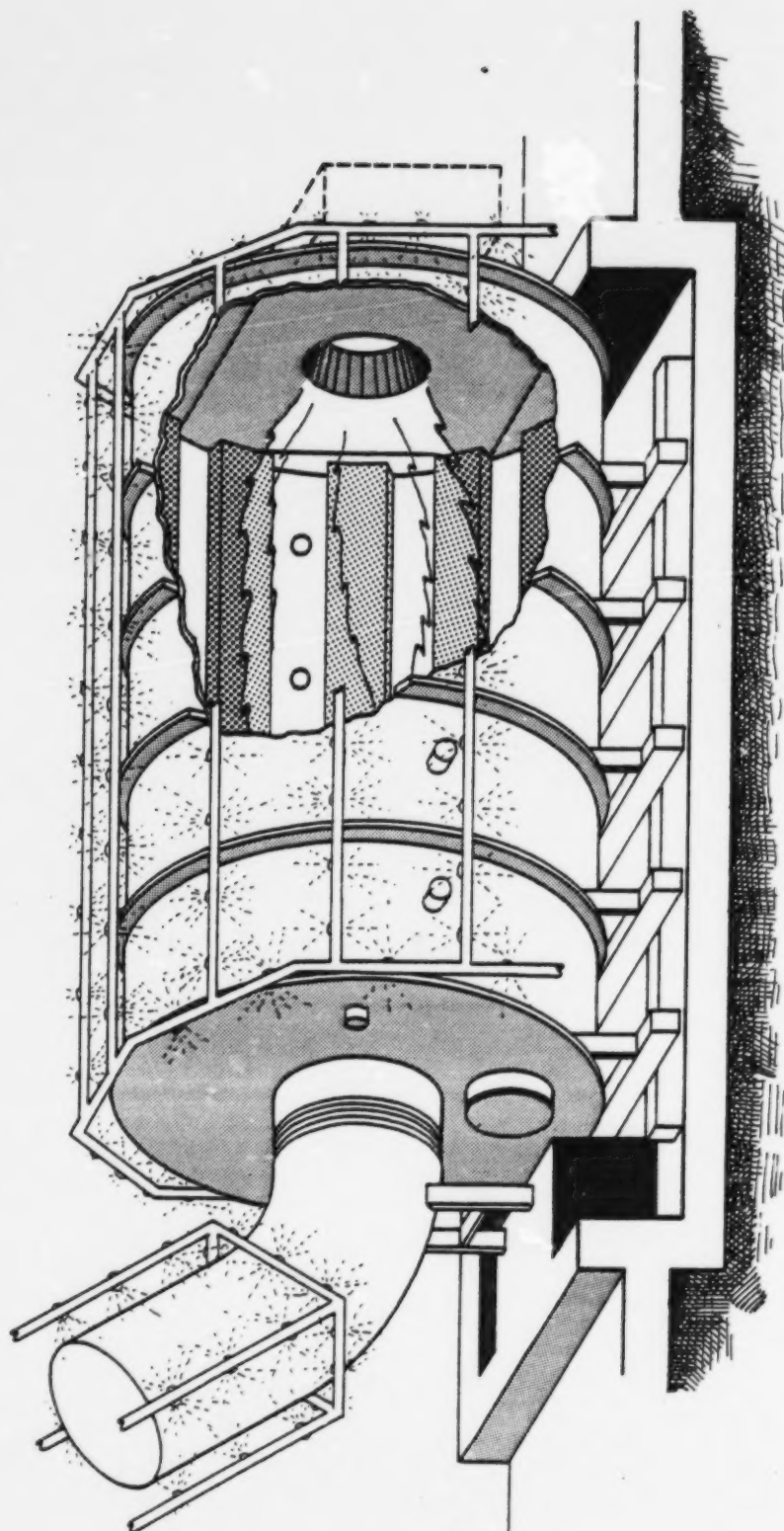


Figure 3-1. Medium Tunnel furnace.

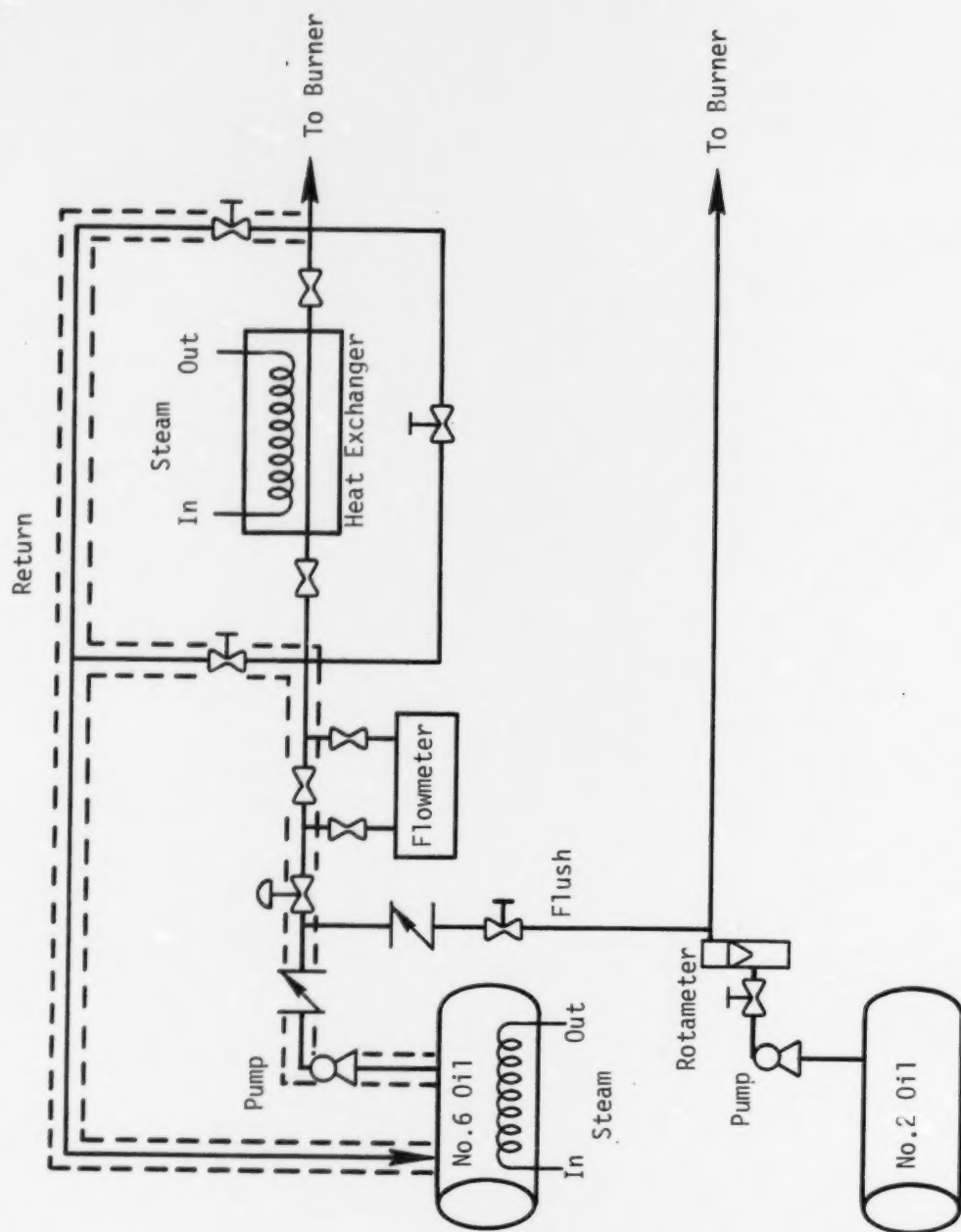


Figure 3-2. MT facility oil-feed system.

TABLE 3-1. CONTINUOUS GAS ANALYSIS INSTRUMENTS

GAS MEASURED	DETECTION PRINCIPLE	MANUFACTURER	MODEL NO.	RANGE
NO, NO ₂	Chemiluminescent	Thermo Electron Corp. (TECO)	10 AR	0-1000 ppm
CO	Non-dispersive Infrared (NDIR)	Anarad, Inc.	AR500R	0-500 ppm
CO ₂	Non-dispersive Infrared (NDIR)	Anarad, Inc.	AR500R	0-25%
O ₂	Paramagnetic	Taylor Servomex	0A-272	0-10%
SO ₂	Non-dispersive Ultra-violet	Dupont	400	0-2000 ppm

Table 3-2 compares the characteristics of the MT furnace and the host steam generator. The MT is 1.5 m (5 ft.) larger in diameter and 4.3 m (14 ft.) shorter in length than the field steam generator, and the total furnace volume is 14 percent greater. Measured gas temperature at the MT furnace exit is slightly hotter than expected for the field steam generator radiant section exit gas temperature. The overall thermal environment is similar in terms of volumetric heat release and furnace efficiency. Surface heat flux calculations for the MT furnace and steam generator are not directly comparable since only that portion of the MT furnace surface not covered by refractory is considered as cooled surface.

The net impact of the differences between the two furnaces on NO_x and smoke emissions is expected to be small since thermal environment is similar. The impact of the differences in flame confinement (i.e., L/D) may cause NO_x and smoke emissions to be slightly different in the MT furnace than in the field, especially under conditions where the flame is very long and flame impingement on cooled surfaces occurs.

TABLE 3-2. FURNACE CHARACTERISTICS

PARAMETER	MEDIUM TUNNEL	TEOR STEAM GENERATOR
<u>Firing</u>		
Configuration		
Capacity	Single Wall 23 MW (80 x 10 ⁶ Btu/hr) 9 MW (30 x 10 ⁶ Btu/hr)	Single Wall 16.3 MW (55.8 x 10 ⁶ Btu/hr) 4.1 MW (14.0 x 10 ⁶ Btu/hr)
<u>Dimensions</u>		
Shape		
Diameter	Horizontal Cylinder	Horizontal Cylinder
Length	4.3 m (14 ft.)	2.7 m (9 ft.)
Volume	6.4 m ³ (21 ft. ³)	11 m ³ (35 ft. ³)
Surface Area	87 m ² (3079 ft. ²) 44 m ² (475 ft. ²) 66 m ² (713 ft. ²) 110 m ² (1188 ft. ²)	76 m ³ (2700 ft. ³) - - -
<u>Thermal Environment*</u>		
Cooling		
Exit Temperature	Water Sprays on Exterior Surfaces 1150°C (2100°F)	Steam Tubes 980°C (1800°F)
Heat Release/Cooled Surface	0.37 MW/m ² (117,474 Btu/hr ft. ²)	0.09 MW/m ² (28,000 Btu/hr ft. ²)
Heat Release/Volume	0.19 MW/m ³ (18,100 Btu/hr ft. ³)	0.21 MW/m ³ (21,000 Btu/hr ft. ³)
Radiant Zone Heat Flux	0.19 MW/m ² (58,810 Btu/hr ft. ²)	0.05 MW/m ² (16,000 Btu/hr ft. ²)
Furnace Efficiency	50%	58%

* Based on 16.3 MW Thermal Input

4.0 PRELIMINARY EVALUATION TESTS

The objectives of these tests were to:

- cure the refractory under controlled conditions
- evaluate control system operation/response and establish input/output factors
- establish the impact of burner settings on emissions and flame shape
- evaluate overall mechanical and thermal performance

The initial heat-up of the refractory lining was conducted over a four-day period in accordance with instructions provided by the refractory supplier and installer. After completing the curing, the burner was fired on residual oil at full load, followed by 60 hours of continuous testing.

The input and output parameters listed in Tables 4-1 and 4-2 were measured and recorded for each test condition. The fuel used for all of the test results presented here was a residual fuel oil derived from California crude oil. Table 4-3 presents ultimate analyses, viscosity, API gravity, and heating value data for this oil. Nitrogen content was 0.74 percent and sulfur content was 1.37 percent. This oil is slightly less viscous than the Kern Front crude oil (Figure 4-1) which is fired at the field demonstration site and requires pre-heating to 105°C for atomization compared to 115°C for the crude oil.

Table 4-4 lists the nominal operating conditions and range of parameters investigated during the tests. First-stage input parameters which were varied included stoichiometry, air register setting (swirl), oil gun setback, atomizer spray angle, and stabilizer. Second-stage input parameters included excess air, secondary air distribution through the radial and axial ports, and number of secondary air ports. Since TEOR steamers normally operate near full load, the majority of testing was conducted at full load. Several reduced load tests were also conducted. The operating time under staged conditions at reduced loads below 50 percent was kept to a minimum since shell temperatures increased rapidly under these conditions.

The test results are presented in the following section in two parts; combustion performance and hardware performance. Because of fuel pressure limitations of the facility oil system, only 96 percent of full load was achieved during these tests.

TABLE 4-1. INPUT MEASUREMENTS (CONTROLLED VARIABLES)

TYPE	#	PARAMETER	METHOD	# OF MEASUREMENT LOCATIONS
Input	1	Fuel Flow Rate	Turbine Meter and Readout	1
	2	Fuel Temperature	Thermocouple and Dial Thermometer	3
	3	Fuel Pressure	Dial Gauges	3
	4	Primary Air Flow Rate	Pitot Tube	1
	5	Primary Air Pitot ΔP	Pressure Transducer + Readout	1
	6	Primary Air Swirl Setting	Handle Position	1
	7	Secondary Air Flow Rate	Pitot Tube	1
	8	Secondary Air Pitot ΔP	Pressure Transducer + Readout	1
	9	Secondary Air Radial/Axial Distribution	Damper Positions	9
	10	Atomizing Fluid Pressure	Dial Gauges	2
	11	Atomizing Steam Pressure	Dial Gauges	2
	12	Oil Gun Position	Tape Measure	1
	13	Blower Damper Position	Handle Position	1

TABLE 4-2. OUTPUT MEASUREMENTS

TYPE	#	PARAMETER	METHOD	# OF LOCATIONS
Output	1	Exhaust Gas - O ₂ (%)	Paramagnetic Analyzer - Taylor	1
	2	- NO/NO _x (ppm)	Chemiluminescent - TECO	1
	3	- CO (ppm)	NDIR - Anarad	1
	4	- CO ₂ (%)	NDIR - Anarad	1
	5	- Smoke	Smoke Spot - Racharach	1
	6	Furnace Exit Temperature	Suction Pyrometer - K-Type + Datalogger	1
	7	Suction Pyrometer Flow	Orifice Meter, Manometer + Dial Gauge	2
	8	First-Stage Exit Temperature	Suction Pyrometer - S-Type + Readout	1
	9	Flame Shape + Length	TV Camera, Visual Observation	3
	10	Burner Shell Temperature	K-Type Thermocouples + Datalogger	20
	11	Primary Air Register Temperature	K-Type Thermocouples + Datalogger	1
	12	Primary Air Preheat Temperature	K-Type Thermocouples + Datalogger	1
	13	Control Setpoint Pressure	Dial Gauge	1
	14	Primary Air Damper Actuator Pressure	Dial Gauge, Vertical Gauge	2
	15	Primary Air Damper Actuator Position	Pointer + Scale	1
	16	Secondary Air Damper Actuator Pressure	Dial Gauge, Vertical Gauge	2
	17	Secondary Air Damper Actuator Position	Pointer + Scale	1
	18	Air Supply Pressure	Static Pressure Probe & Manometer	1
	19	Primary Duct Pressure	Manometer	1
	20	Burner Chamber Pressure	Manometer	1
	21	Primary Register Pressure	Static Pressure Probe & Manometer	1
	22	Secondary Duct Pressure	Manometer	1
	23	MT Pressure	Manometer	1
	24	Fuel Valve Position	Pointer + Scale	1

TABLE 4-3. ANALYSIS OF RESIDUAL FUEL OIL TESTED
IN FULL-SCALE BURNER TESTING

Specific Gravity @ 15°C	0.974
Ultimate Analysis (wt %)	
Carbon	85.07
Hydrogen	11.30
Nitrogen	0.74
Sulfur	1.37
Ash	0.03
Oxygen (by difference)	1.49
Viscosity (cp)	
@ 60°C	197
@ 99°C	29
Heat of Combustion (KJ/g)	
Gross	42.70
Net	40.30

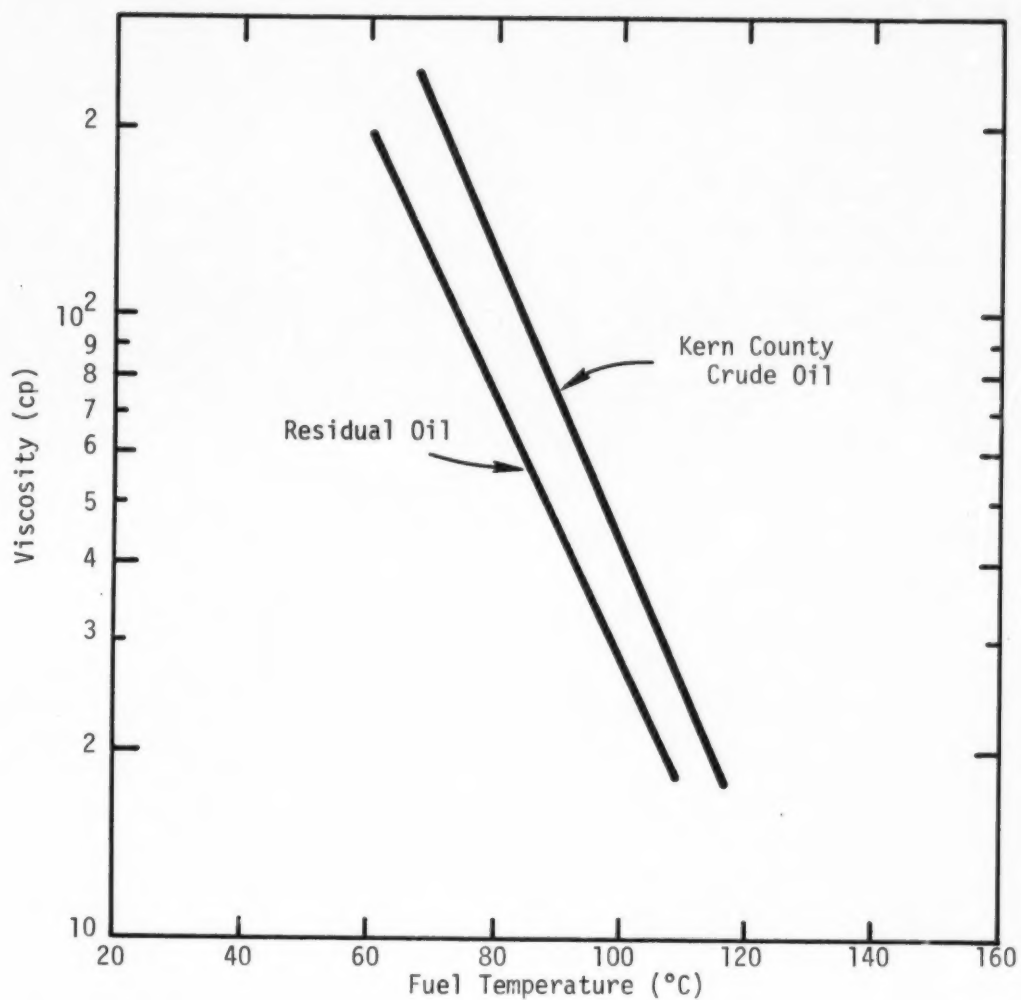


Figure 4-1. Comparison of fuel temperature effect on fuel viscosity for the residual fuel oil tested and a typical Kern County crude oil.

TABLE 4-4. RANGE OF VALUES FOR INVESTIGATED PARAMETERS

PARAMETERS	NOMINAL DESIGN VALUE	RANGE INVESTIGATED
Thermal Load (MW)	16.3	3.9 to 15.7
Fuel Flow (kg/s)	0.38	0.092 to 0.37
Fuel Temperature (°C)	108	113 to 136
Fuel Pressure (k Pa)	793	276 to 793
Atomizer Type	Internal Mixing	-
Spray Angle	90°	50°, 70°, 90°
Atomizing Fluid	Steam	Air, Steam
Atomizing Fluid Differential Pressure (kPa)	138	70 to 210
Primary Throat Diameter (m)	0.38	-
Primary Air Flow Rate (kg/s)	3.2	0.75 to 3.6
Primary Air Swirl No.	0.4	0.3 to 0.90
Stabilizer	28 cm Diffuser	With, Without
Primary Stoichiometry	0.60	0.50 to 0.70
Secondary Air Flow Rate(kg/s)	3.0	1.1 to 3.5
Radial/Axial Distribution	50/50	0/100 to 67/33
No. of Open Radial Ports	8	0, 4, 8
No. of Open Axial Ports	16	8, 12, 16
Overall Excess Air (%)	16	5 to 17

4.1 Results - Combustion Performance

NO emissions data are corrected to zero percent oxygen using the relationship:

$$[\text{NO}]_{0\% \text{O}_2} = [\text{NO}]_{\text{measured, dry basis}} \cdot \frac{21}{21 - [\text{O}_2]_{\text{measured, dry basis}}}$$

or alternatively, where specified, to 3 percent oxygen:

$$[\text{NO}]_{3\% \text{O}_2} = [\text{NO}]_{\text{measured, dry basis}} \cdot \frac{21-3}{21 - [\text{O}_2]_{\text{measured, dry basis}}}$$

CO emissions are corrected similarly. All gaseous emissions are reported on a dry basis unless otherwise noted, test conditions correspond to the nominal conditions given in Table 4-4.

4.1.1 First-Stage Effects

Figure 4-2 illustrates the effect of first-stage stoichiometric ratio (SR_1) on NO_x , CO, and smoke emissions for two primary air register (swirl) settings and with the large conical diffuser attached to the oil gun. The low swirl setting shown in the figure corresponds to the maximum register opening (minimum swirl setting) which would produce acceptable flame stability/ignition characteristics. Secondary air was divided approximately evenly between 16 axial air ports and 4 radial air ports. Overall excess oxygen was maintained constant at 3 percent, and fuel input was 16.1 MW thermal. NO_x emissions reached a minimum value of approximately 87 ppm at $\text{SR}_1 = 0.59$ for swirl number (S) = 0.3. Increasing swirl to $S = 0.7$ (by closing the register doors) did not significantly affect either minimum NO_x or the dependence on SR_1 . NO_x emissions were only mildly sensitive to SR_1 , ranging from 87 to 110 ppm for $0.59 \leq \text{SR}_1 \leq 0.68$ and from 108 to 87 ppm for $0.51 \leq \text{SR}_1 \leq 0.59$. Smoke emissions were strongly dependent on SR_1 with low swirl ($S = 0.3$) and increased sharply as SR_1 was decreased. When swirl was increased to $S = 0.7$, smoke emissions decreased and were nearly constant at a smoke number of 5 for $0.51 \leq \text{SR}_1 \leq 0.63$.

Visual observations of the second-stage flame for these two conditions showed that the flame was orange (sooty) in appearance and that at low swirl, the tail of the flame could be seen entering the exhaust duct of the MT furnace. The high smoke numbers measured for this configuration are attrib-

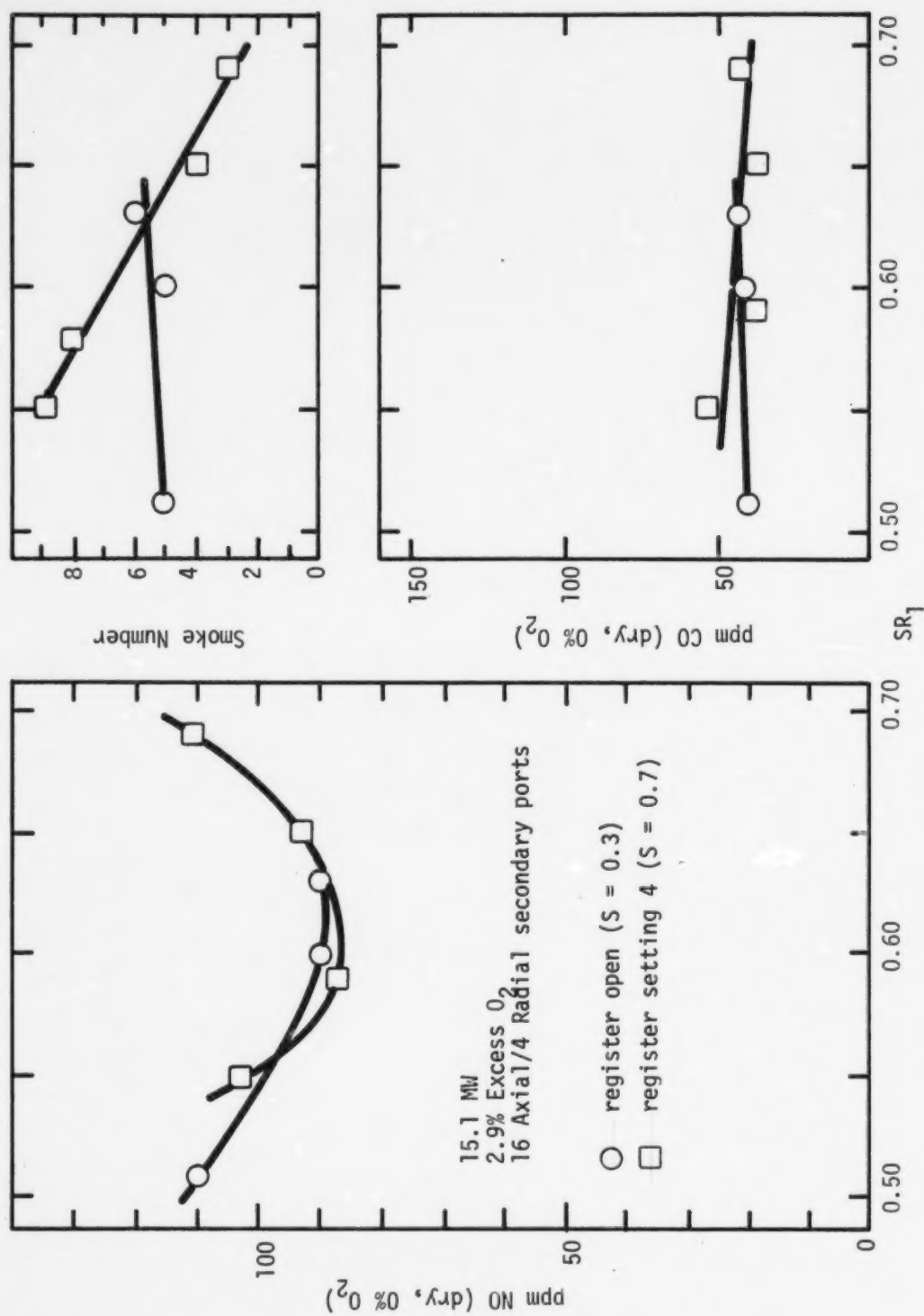


Figure 4-2. Effect of primary register setting (swirl level) on emissions.

uted to quenching of the second-stage flame tail in the exhaust duct, preventing burnout of soot formed in the flame. Increasing the swirl level noticeably decreased second-stage flame length to approximately 5 meters; however, the periphery of the flame was still smokey and uneven in appearance, which appeared to be related to the use of the radial air ports (discussed in Section 4.1.2).

CO emissions under these conditions were generally very low (<40 ppm), except where smoke number was high and substantial flame quenching in the exhaust duct occurred.

With the diffuser attached to the oil gun, swirl could not be increased above $S = 0.7$ without restricting primary air flow due to the imposed pressure drop. When the diffuser was not attached to the oil gun, a higher register setting ($S = 0.9$) was required to maintain a stable flame; lower swirl levels produced severe oscillations at the burner, and at higher swirl levels sufficient air flow could not be supplied. Figure 4-3 compares emissions achieved without the diffuser at $S = 0.9$ and with the diffuser at the minimum swirl level ($S = 0.3$). Both sets of data were obtained with all of the secondary air injected through the 16 axial ports. Minimum NO_x emissions were 63 ppm without the diffuser at $S = 0.9$ and 75 ppm with the diffuser at $S = 0.3$. Optimum stoichiometry was similar in both cases. Smoke emissions were much lower for the case without the diffuser. Comparing Figures 4-2 and 4-3, the difference in smoke number seems attributable to the level of swirl, although the effect is much greater in Figure 4-3 than in Figure 4-2. The swirl number calculated for this air register does not take into account the effect of diffuser. The presence of a center body has been shown (Syred and Beer, 1974) to reduce angular momentum at the burner exit, thus swirl may be somewhat weaker than calculated values with the diffuser. This plus the fact that higher register settings (therefore swirl) could be achieved without the diffuser may account for the comparatively large impact on smoke emissions shown in Figure 4-3.

The difference in smoke emissions for the data of Figure 4-3 is attributed to the effect of primary configuration on second-stage flame length. The second-stage flame produced with the diffuser ($S = 0.3$) was very long and, at the optimum SR_1 , extended well into the MT furnace exhaust duct. The flame was yellow-orange and opaque in appearance and the diameter of the flame was clearly defined. The diameter of the flame was approximately 2 meters. The

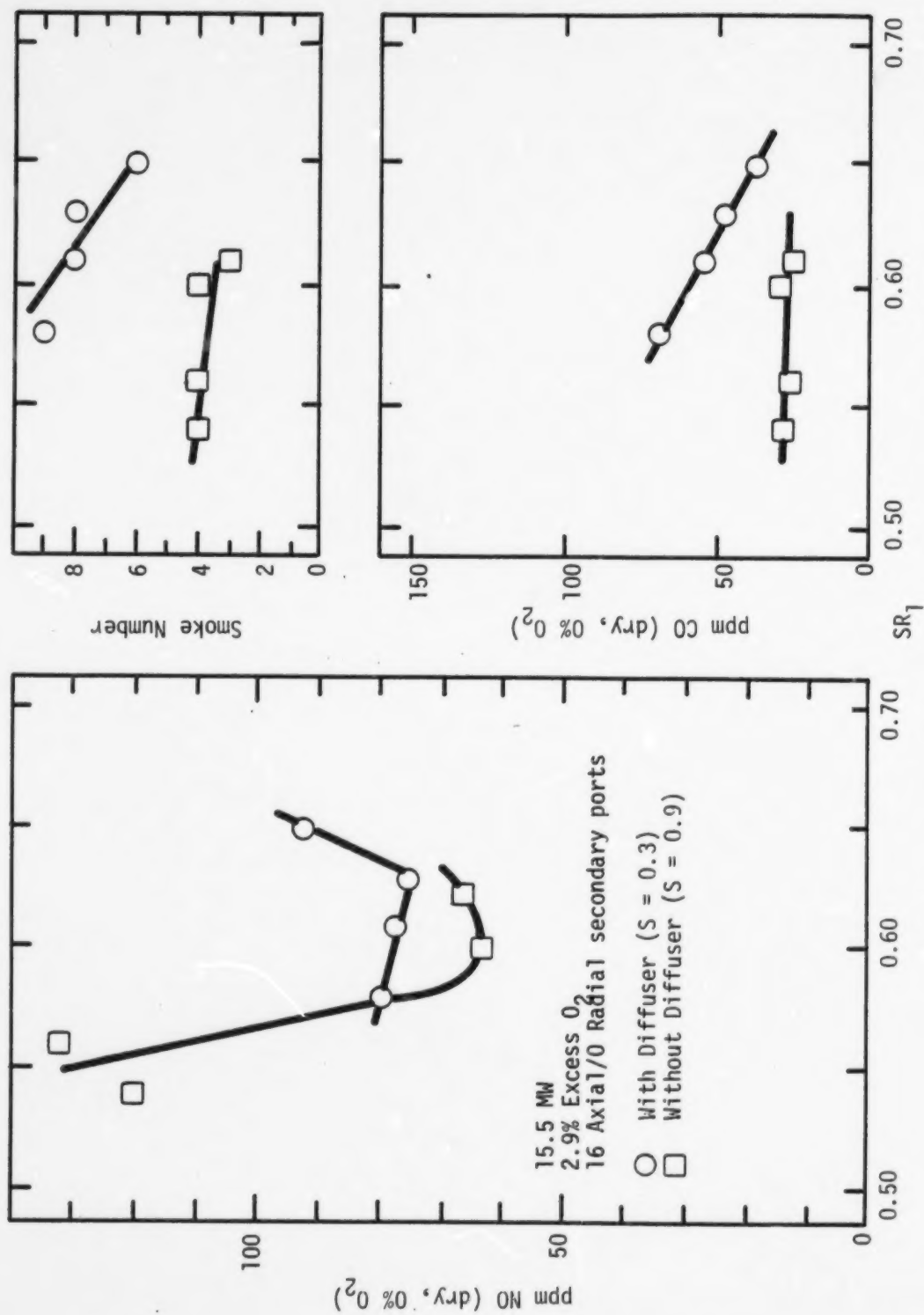


Figure 4-3. Effect of primary configuration on emissions.

second-stage flame produced without the diffuser ($S = 0.9$) was much shorter and the majority of the second-stage flame was just entirely contained within the MT furnace. Occasionally, part of the flame tail reached into the exhaust duct. Again, conditions with high smoke numbers were associated with long flames extending into the furnace exhaust duct, where quenching occurred.

Other first-stage variables investigated were oil gun setback and atomizer spray angle and type. Oil gun position had no effect on NO_x or smoke emissions. Without the diffuser attached, inserting the oil gun into the throat beyond a critical point caused the flame to go unstable. Stability was generally very good when the oil gun was positioned behind this critical point. Stability was very good at all oil gun positions with the diffuser.

Two alternative tips for the internal mixing atomizer were briefly tested without the diffuser. These tips produced included spray angles of 70° and 50° . A full-load flame could not be stabilized with these spray angles under any combination of oil gun position and swirl level. Similar results were achieved using an ultrasonic atomizer with a very narrow ($\sim 15^\circ$) spray angle. These atomizers could not be tested with the diffuser since it was destroyed early in the test series, and no replacement was available.

4.1.2 Second-Stage Effects

Two second-stage parameters were varied during the burner trials: excess air level and secondary air injection configuration. Figure 4-4 shows the effect of excess oxygen level on NO_x and smoke emissions for one configuration. NO_x emissions decreased from 133 ppm to 120 ppm as excess oxygen was reduced from 2.8 percent to 1.0 percent. Smoke number jumped from 2 to 6 below 2.8 percent excess oxygen. It was not clear from flame observations why smoke number was strongly affected.

Secondary air was injected through both radial and axial ports during these tests; the distribution between ports and the number of open ports was varied. The specific secondary port configurations investigated during these trials are given in Table 4-5. Calculated jet velocity is also given. The distribution of air flow is based on measurement of windbox air pressure and damper open area.

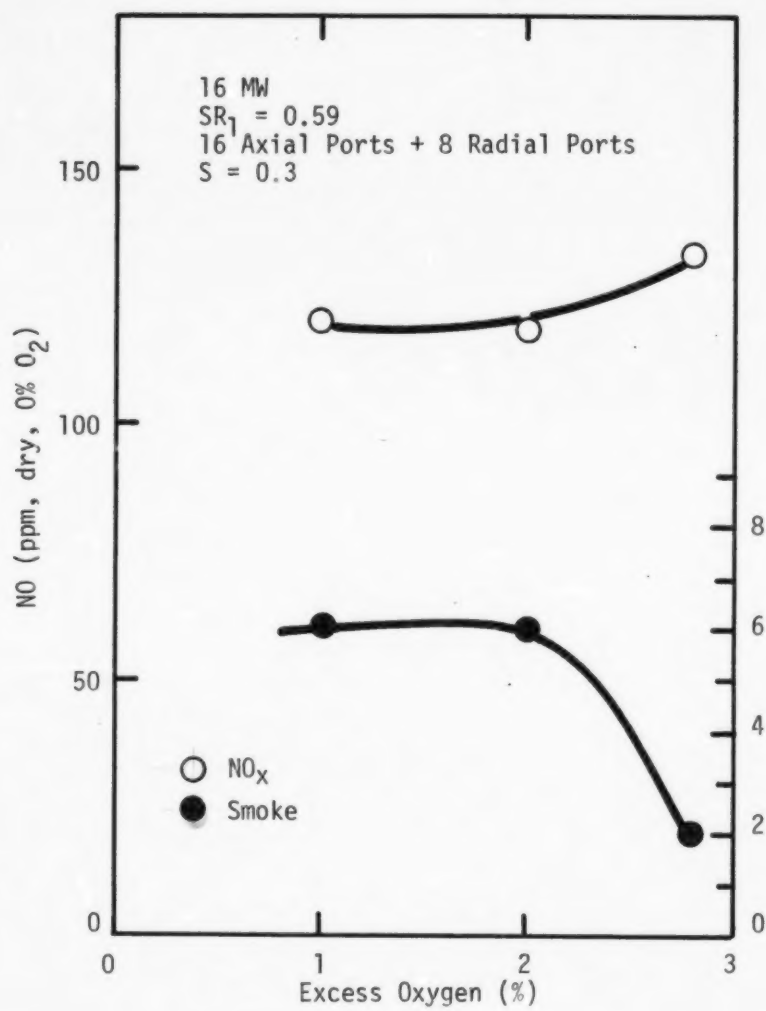


Figure 4-4. Effect of excess O_2 on NO_x and smoke emissions.

TABLE 4-5. SECONDARY AIR INJECTION PORT ARRANGEMENTS TESTED

SECONDARY AIR DISTRIBUTION (% RADIAL/% AXIAL)	AXIAL PORTS		RADIAL PORTS		PRIMARY CONFIGURATION
	NUMBER OF PORTS	CALCULATED* VELOCITY (M/S)	NUMBER OF PORTS	CALCULATED VELOCITY (M/S)	
67/33	16	14	8	28	With Diffuser $S = 0.3$ →
67/33	16	14	4	56	
33/67	16	28	4	28	Without Diffuser $S = 0.9$ →
0/100	16	42	0	-	
0/100	12	56	0	-	
0/100	8	84	0	-	

* Calculated for $SR_1 = 0.6$, 3% O_2 , 16.1 MW thermal input, and 50°C air temperature.

Emissions results showing the effect of radial port variations are given in Figure 4-5 for the primary configuration with the diffuser and $S = 0.3$. The number of radial ports and the amount of secondary air injected through them had a very strong effect on both NO_x and smoke emissions. Minimum NO_x emissions were initially reduced from 133 ppm to 117 ppm by reducing the number of radial ports from 8 to 4, keeping the ratio of axial to radial air at 1:2 (configurations A and B). This decrease in NO_x was accompanied by an increase in smoke number from 2 to 5 and the sensitivity of smoke emissions to SR_1 substantially increased. Optimum SR_1 appeared to shift to slightly leaner stoichiometry. Changing the distribution of secondary air to decrease the amount of radial air (configurations B and C) produced a sharp decrease in NO_x emissions to 87 ppm. This decrease in NO_x was also accompanied by increased smoke emission. NO_x emissions reached a minimum of 75 ppm when the radial air ports were completely closed so that all the secondary air was injected through the axial ports; however, smoke number was 8 and CO emissions were beginning to climb at the optimum SR_1 .

Clearly there is a tradeoff between NO_x and smoke emissions for the data shown in Figure 4-5. As the distribution of secondary air was shifted away from the radial ports, NO_x decreased and smoke increased. The lowest NO_x emissions were achieved without any radial air. Figure 4-6 shows the results of varying the number of axial ports in attempting to optimize axial air injection in the absence of radial air. These data were obtained without the diffuser attached to the oil gun and with higher swirl ($S = 0.9$). The difference in emissions resulting from the difference in primary configuration between Figures 4-5 and 4-6 was discussed on page 4-9. The data indicate that as the number of ports was reduced, NO_x emissions decreased slightly and smoke emissions decreased significantly. Visual observations also indicated a decrease in flame length and opacity.

The 12 port configuration produced the lowest NO_x , CO and smoke emissions: 57 ppm NO_x (corrected to 0% O_2), smoke number of 2, and 35 ppm of CO. The flame length decreased steadily as the number of ports was reduced. Figure 4-7 illustrates the main boundaries of the second-stage flame in the 12 and 16 port configuration. The flame diameter was very sharply defined in both cases and was estimated to be 1.8 to 2.2 meters. The tail of the flame occasionally

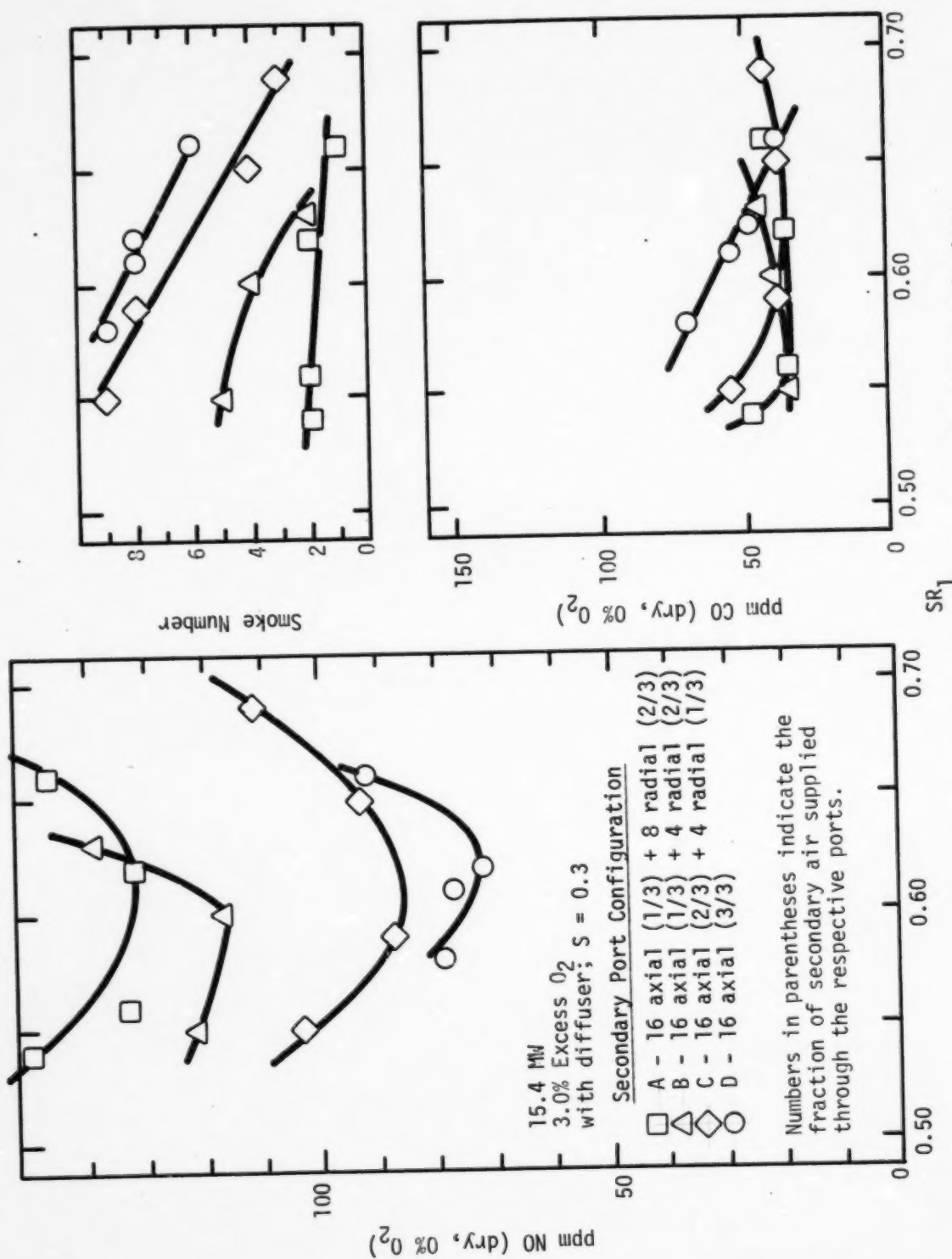


Figure 4-5. Effect of radial secondary air injection on emissions.

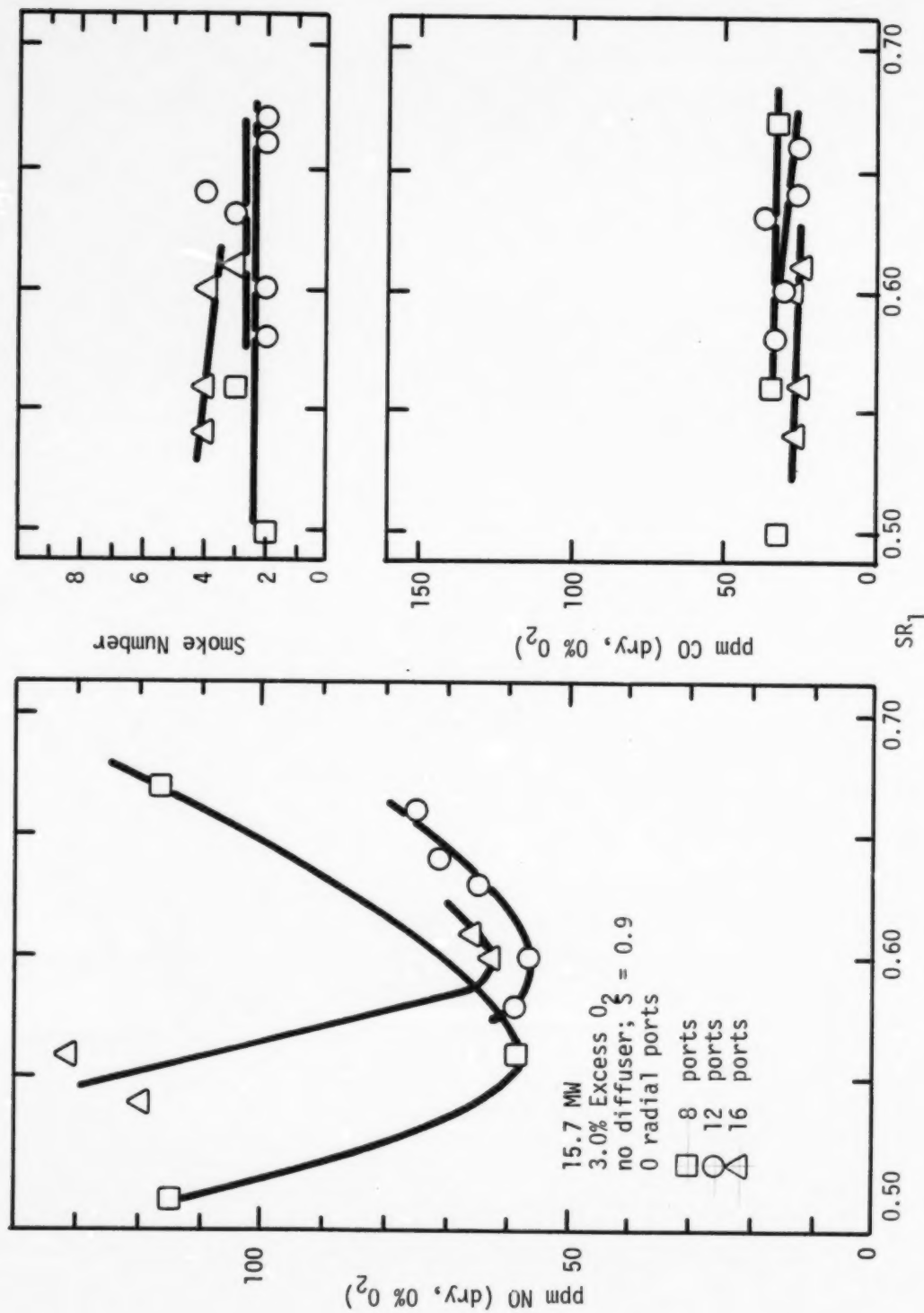


Figure 4-6. Effect of number of axial secondary air ports on emissions.

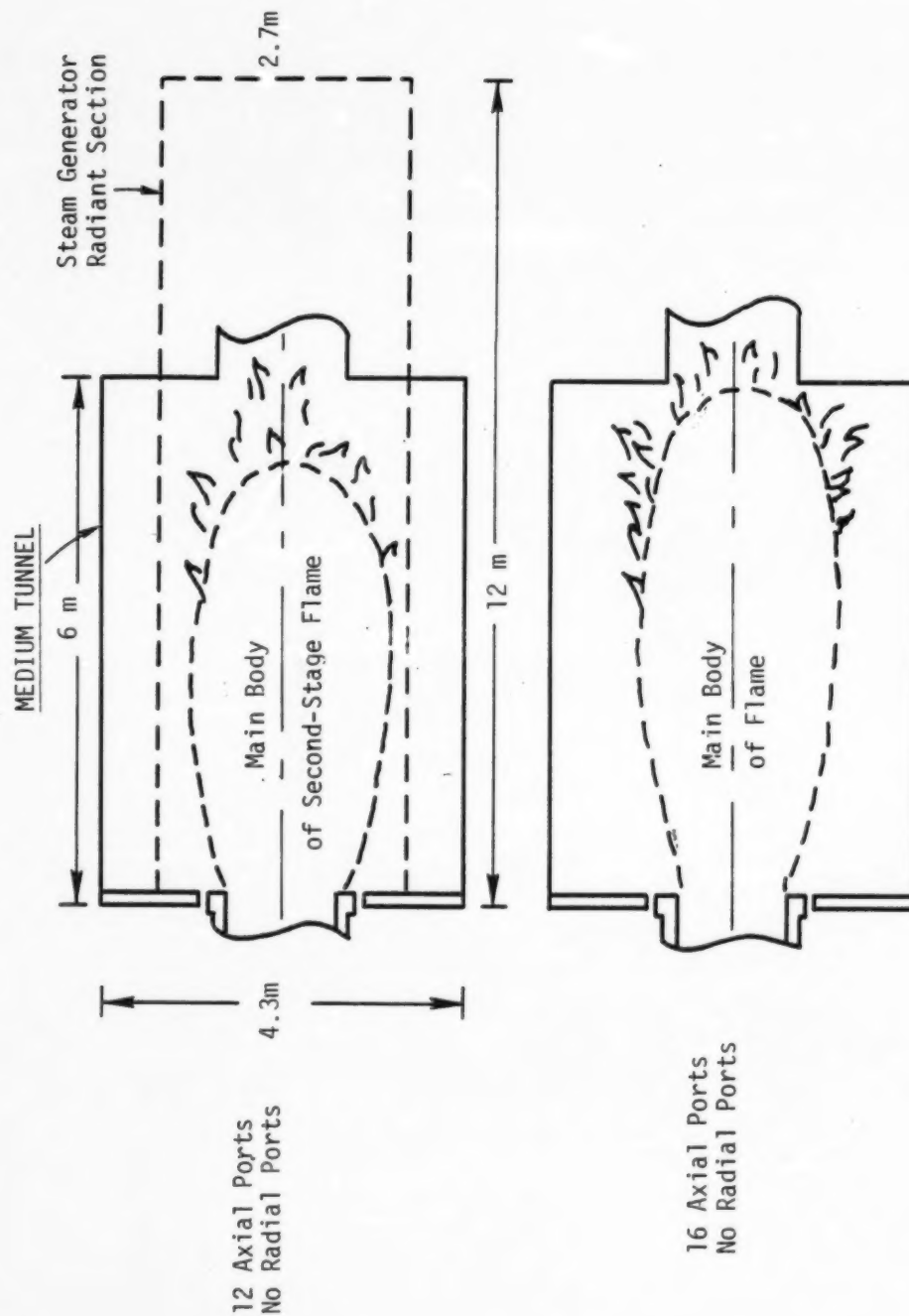


Figure 4-7. Comparison of second-stage flame length observed in the MT for the 12 and 16 axial ports (16 MW, 2.0 - 3.0% O_2).

reached into the MT exhaust duct in the 16 port configuration. The flame was roughly 20 percent shorter in the 12 port configuration and the entire flame was just contained within the MT furnace. Overall flame length for the 12 port configuration was estimated to be 4.5 meters.

These data indicate that adequate control over flame shape is possible through variation of axial port configuration without substantially increasing NO_x emissions. Decreasing the number of axial ports increases the secondary air jet velocity, however the jets are also farther apart. Clearly, increasing jet velocity will increase the rate of mixing through entrainment; however, the inter-jet distance also increases. Both effects may combine to decrease NO_x and smoke emissions.

4.1.3 Turndown (Load) Effects

Although TEOR steam generators normally operate at 80 to 100 percent of full design capacity, the burner must be capable of reduced load operation for light-off and warm-up. Reduced load operation is sometimes required for drying out steamer refractory after washing-down the convective section also. Burner turndown is typically 4 to 1. Figure 4-8 shows emissions from the CP burner between 25 and 100 percent full load. SR_1 was held constant at 0.61 and overall excess oxygen was 3.0 percent except at 25 percent load. Excess oxygen was increased to 7.9 percent at 25 percent load to avoid excessive CO emissions. Emissions decreased from 60 ppm to 38 ppm as load was decreased from 100 percent (15.7 MW) to 50 percent (7.9 MW). This decrease in NO_x is due to increased first-stage residence time at low loads. NO_x emissions at 25 percent load (3.9 MW) were higher than at 50 percent load. SR_1 was not varied during these tests, therefore the burner may not be operating at the optimum (for NO_x) stoichiometry in the first-stage. Previous pilot-scale data showed that optimum SR_1 may shift at reduced load, and this is probably true also for the 25 percent load data shown.

CO and smoke emissions were insensitive to load and remained well within acceptable levels throughout the turndown range.

4.2 Hardware Performance

A major objective of the tests was to characterize the performance of all the burner components and auxiliary equipment and identify potential

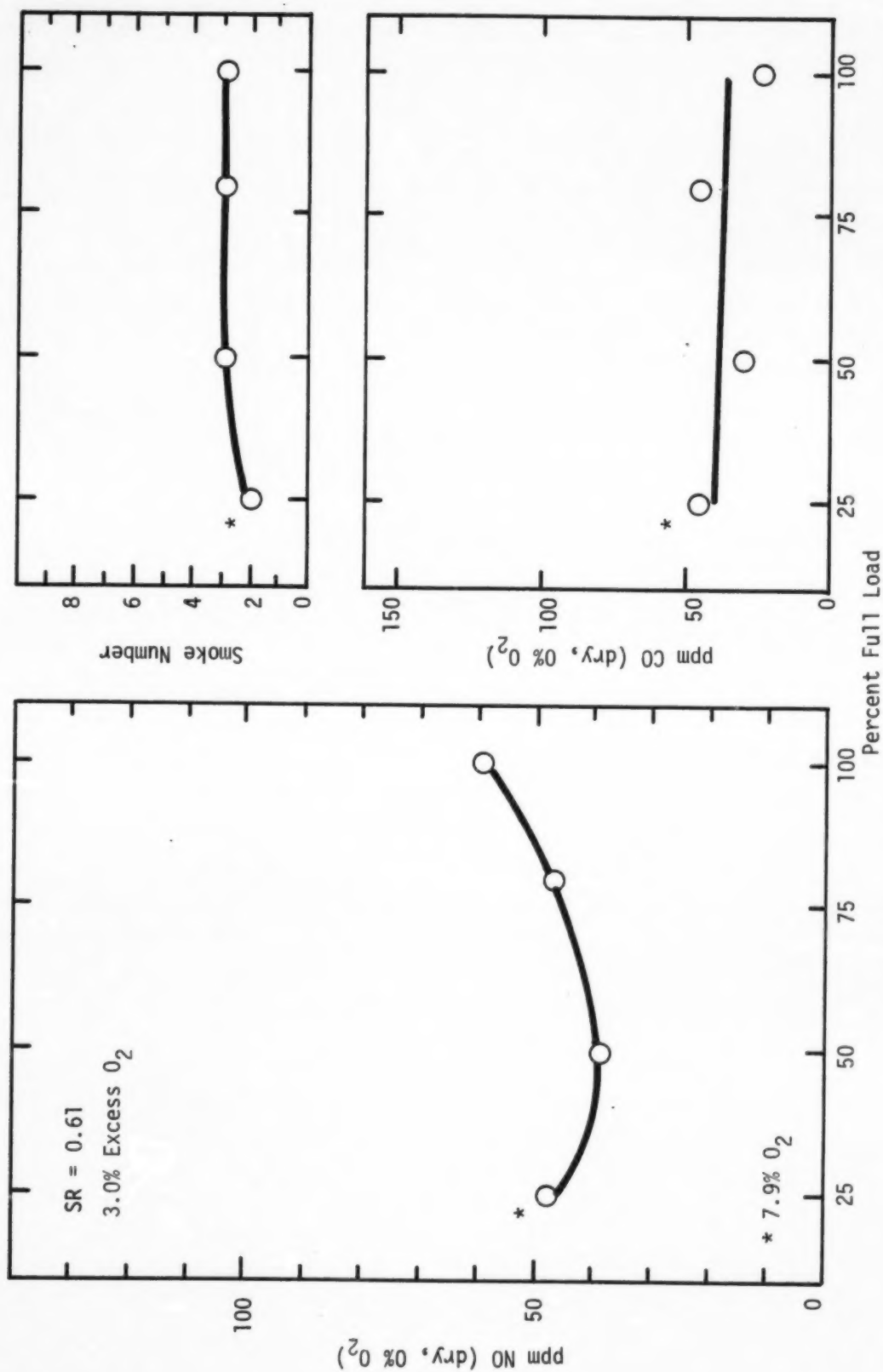


Figure 4-8. Effect of load on emissions (100 percent load = 15.7 MW).

problem or improvement areas. Particular attention was given to the thermo-mechanical performance of the steel shells and refractory lining, since design calculations had indicated potentially destructive conditions could occur under certain operating conditions. The control system was also operated in full-automatic mode for the first time and the overall performance of the system was briefly evaluated. The following discussion highlights the performance of the refractory lining, burner controls, and ancillary components.

4.2.1 Refractory Lining and Steel Shells

Prior to testing, the burner was heated slowly to cure the plastic refractory and mortar used in the brickwork. The initial heat-up is also fairly critical for the brickwork itself, as the lining settles and deforms due to thermal expansion. According to the refractory manufacturer, the bricks deform plastically under stress at high temperature, which produces "built-in" expansion allowance on the initial heat-up. This deformation must occur slowly so that failure stresses are not reached. The plastic refractory (ramming mix) used for the primary throat and first-stage exit also requires slow heat-up to allow moisture to escape slowly and avoid "spalling" (surface fracture) of the lining.

Instrumentation of the lining was limited to thermocouples placed on the inner shell at several locations and one thermocouple located within the lining near the conical exit section (see Figure 4-9). Gas temperature near the hot-face of the refractory at the burner exit was measured using a suction pyrometer.

Figure 4-10 shows the gas temperature heat-up rate specified by the manufacturer and the actual measured temperatures during the initial heat-up. Maximum recommended rate of temperature increase was 27°C/hr. The recommended heat-up rate was closely followed. Figure 4-11 shows the temperature within the refractory lining near the cone exit (see Figure 4-9). At this part of the lining, the 15 cm layer of 90 percent-alumina brick (Greenal-90tm) is backed up by a layer of 43 percent-alumina (KX-99tm) brick. The thermocouple was placed at the interface between the bricks. The interface temperature is shown as a function of hot-face gas temperature during the cure. The interface

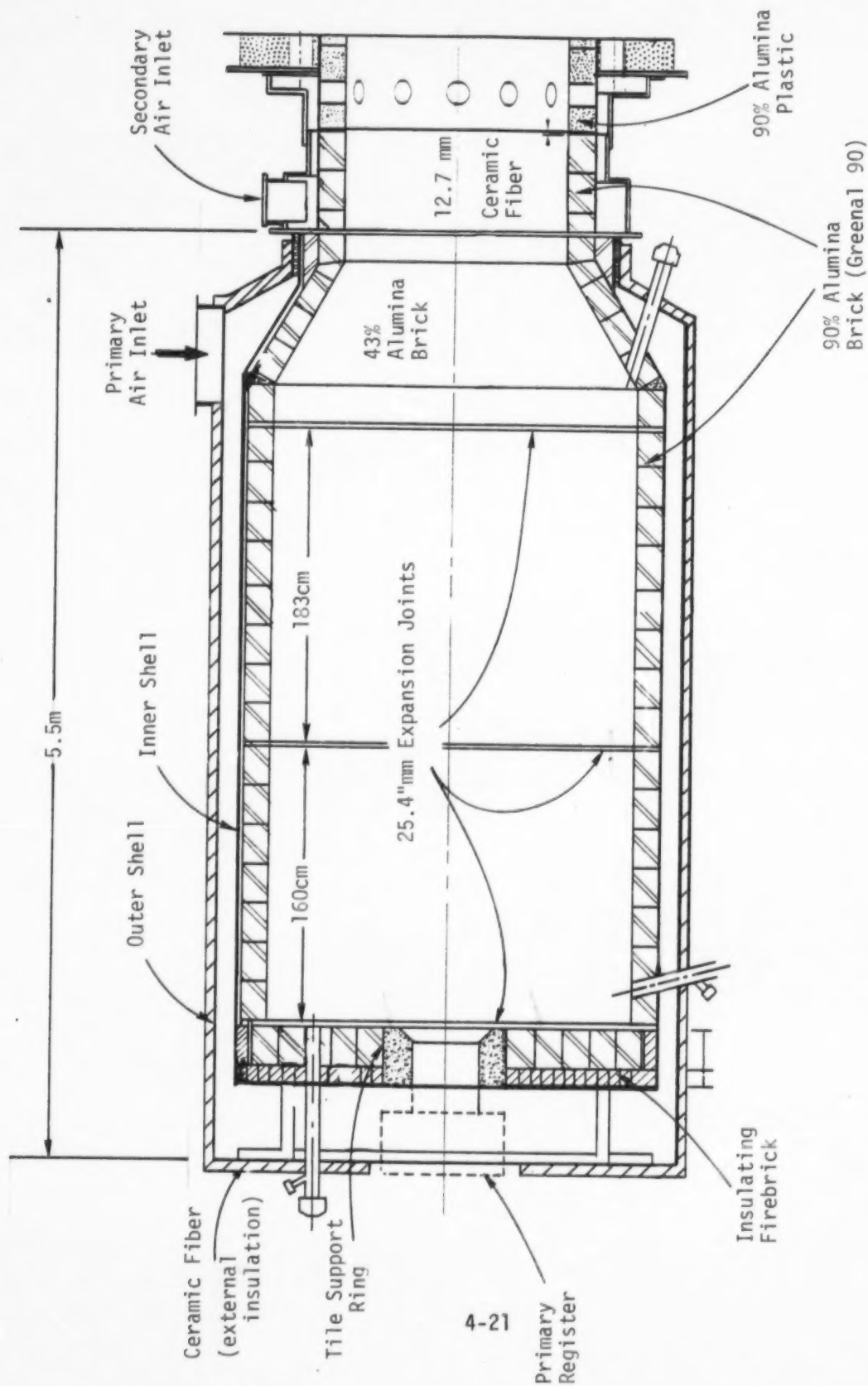


Figure 4-9. TEOR low NO_x Burner.

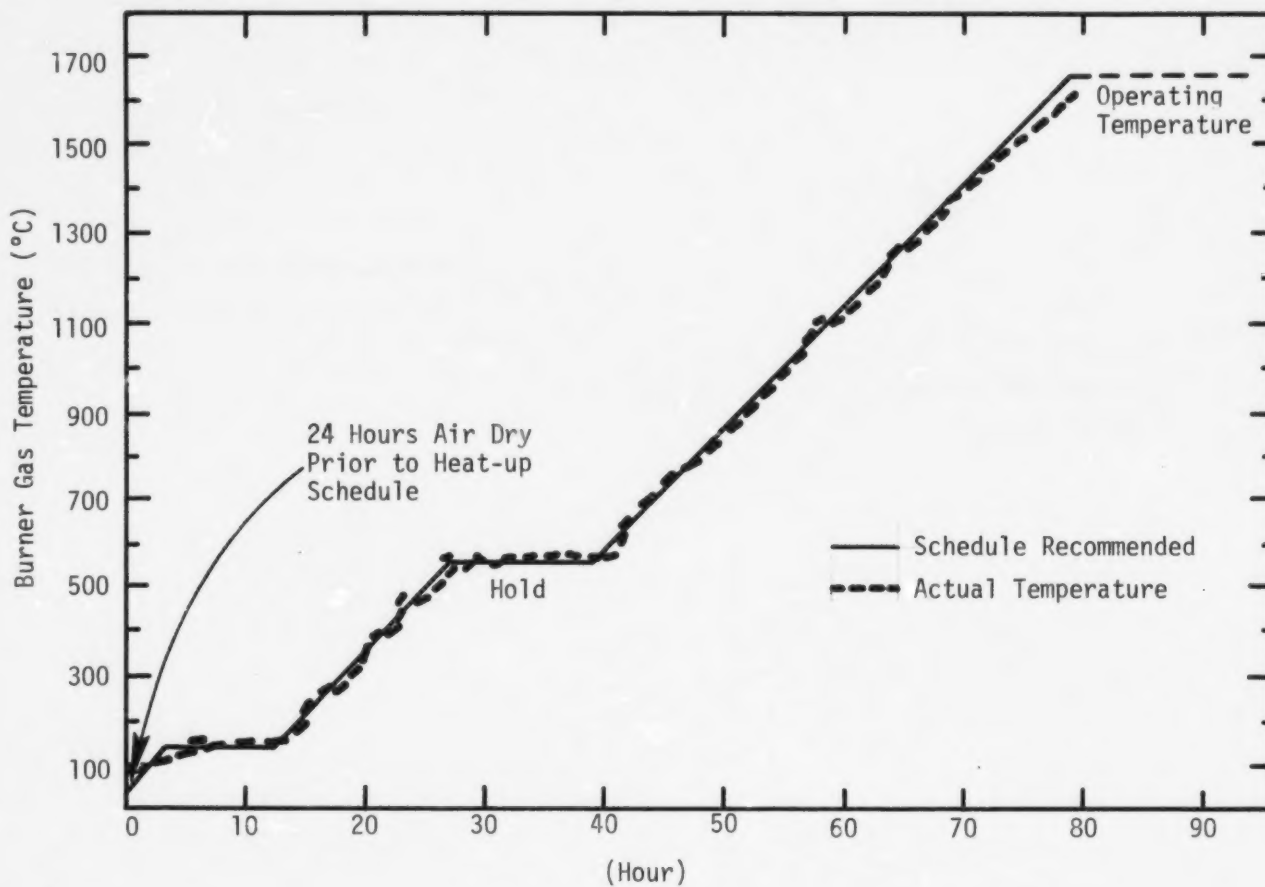


Figure 4-10. Refractory lining curing schedule.

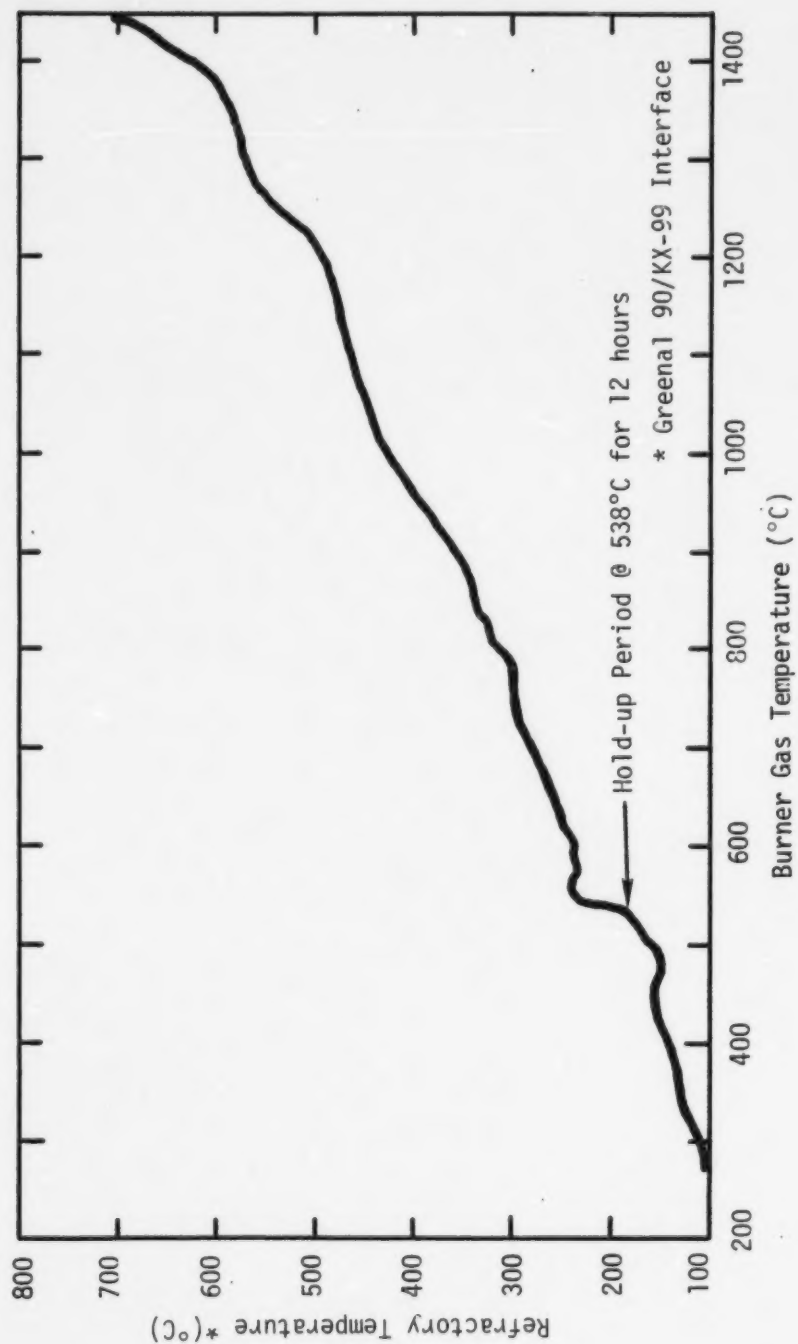


Figure 4-11. Refractory interface temperature vs burner gas temperature near the refractory wall during the curing period.

temperature is expected to lag behind steady-state values due to the thermal inertia of the lining. This inertia was evident during the gas temperature hold period at 500-550°C, where the interface temperature increased from 150 to nearly 250°C in 12 hours.

Figure 4-12 shows the axial inner shell temperature profile at full-load operation. These temperatures were measured by thermocouples inserted through the outer shell into shallow indentations drilled into the surface of the inner shell (see Figure 4-9 for positions). The thermocouples were spring-loaded to maintain good thermal contact as the shells contract and expand. The data shown in the figure represent the average of two or more thermocouples at the same axial location but different circumferential positions. Error bars indicate the range of measured temperatures. Shell temperature near the primary air inlet was quite low (~60°C) as anticipated, and increased toward the front end of the burner to ~230°C as the primary air temperature increased. These measured temperatures are somewhat lower than the design calculations would indicate, which is due in part to the conservative margins allowed for in the calculations. Additionally, some error from the true shell temperature is likely in the measurements since the thermocouples will conduct some heat away from the junction and transfer heat to the air (similar to a fin). In order to assess the magnitude of this error a brief test was conducted in which the burner was completely shut down (including primary air flow) from full load for a two-minute period. At the end of 1 and 2 minutes the shell temperature profiles given in Figure 4-13 were measured. The data suggest that the true shell temperature is probably on the order of 70°C higher than the profile given in Figure 4-12.

The primary air gains heat as it cools the shells, hence the term "regenerative." Preheat measured just upstream of the primary air register was approximately 195°C at optimum full-load conditions. Figure 4-14 shows primary air preheat temperature versus primary air flow at full load. Air temperature reached 215°C at $SR_1 = 0.53$ and decreased to 165°C as SR_1 increased to 0.65. The air preheat at optimum SR_1 represents 0.52 MW or 3.2 percent of the total heat input.

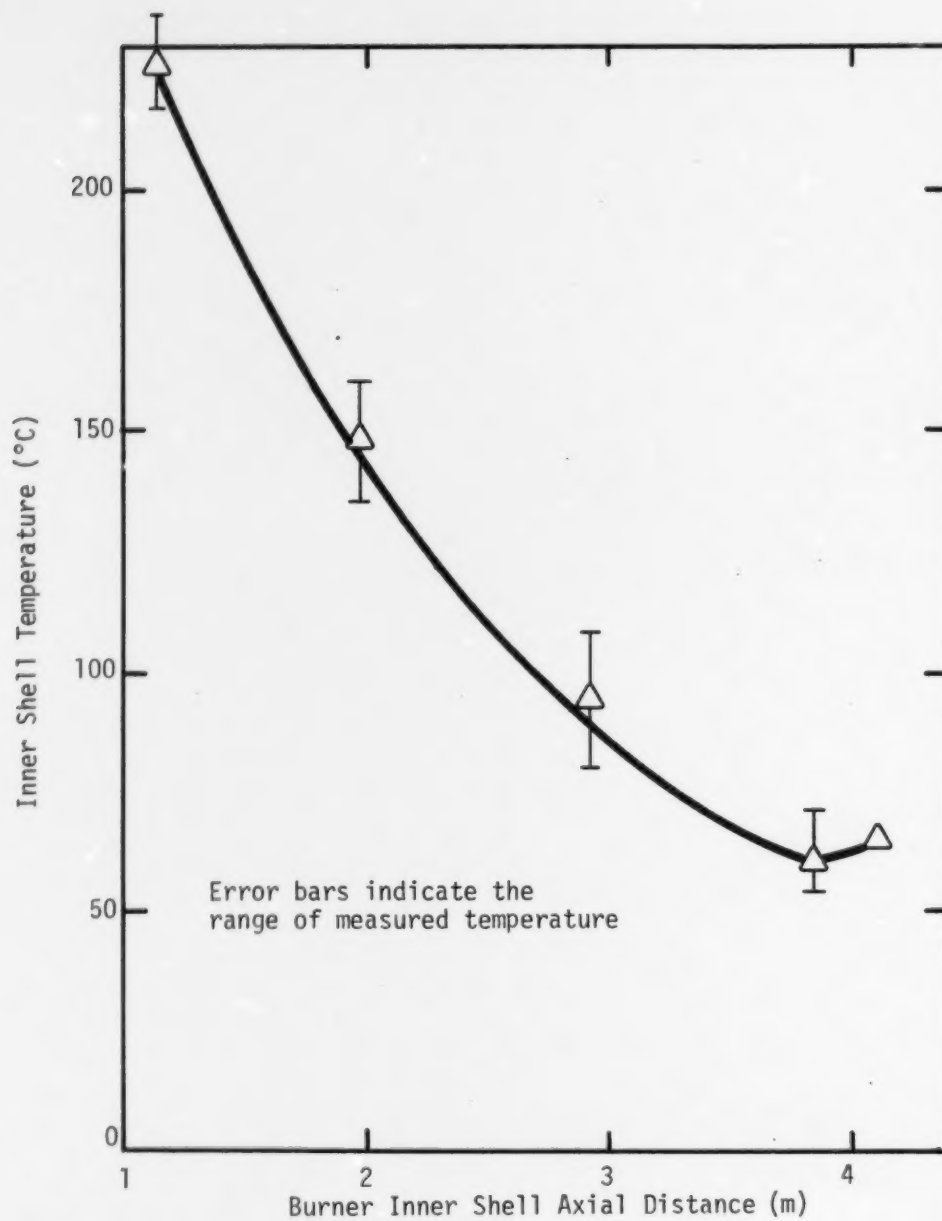


Figure 4-12. Typical inner shell (top half) temperature profiles for full-load operating conditions ($SR_1 \sim 0.6$).

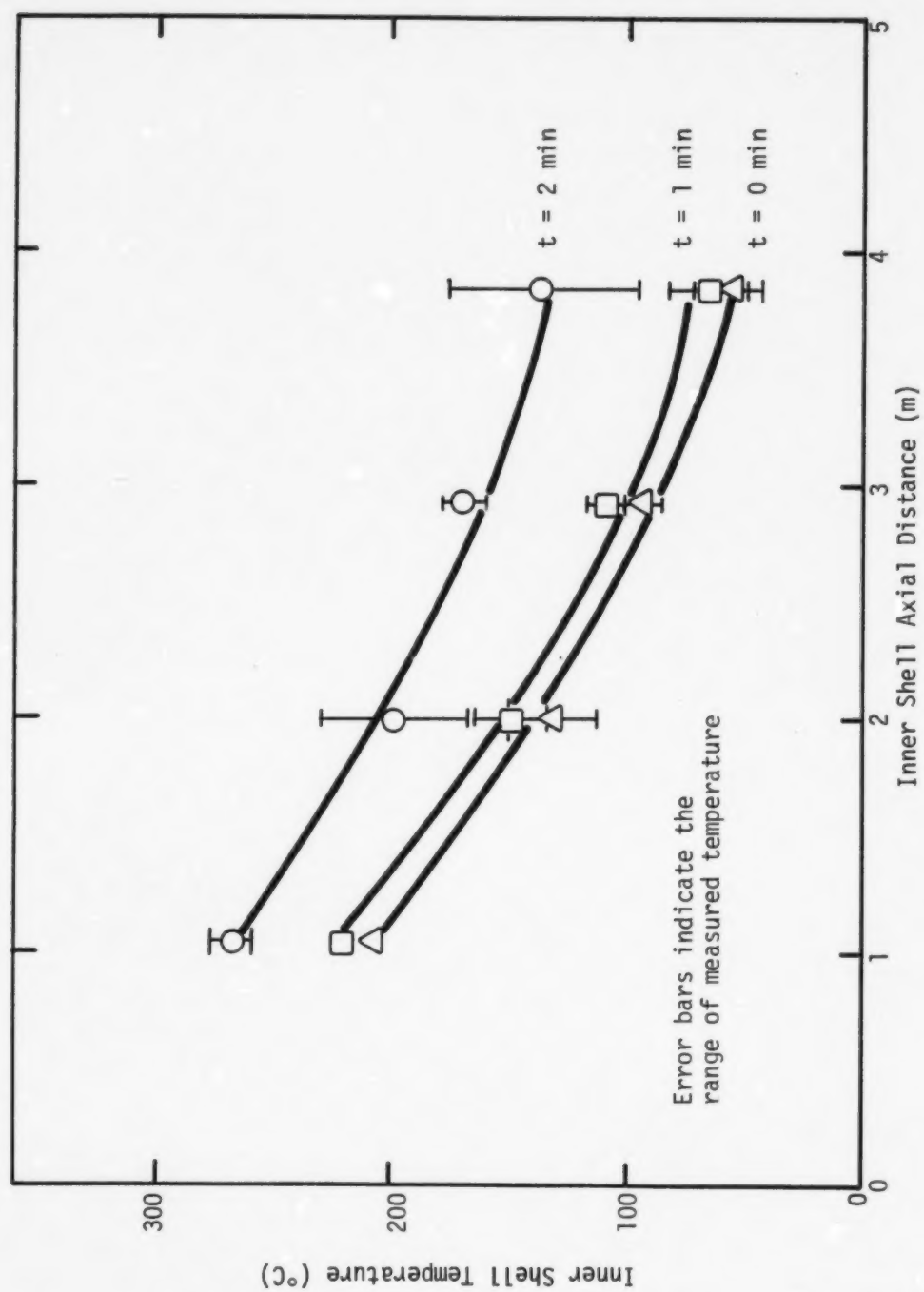


Figure 4-13. Shell temperature profiles after complete burner shutdown.

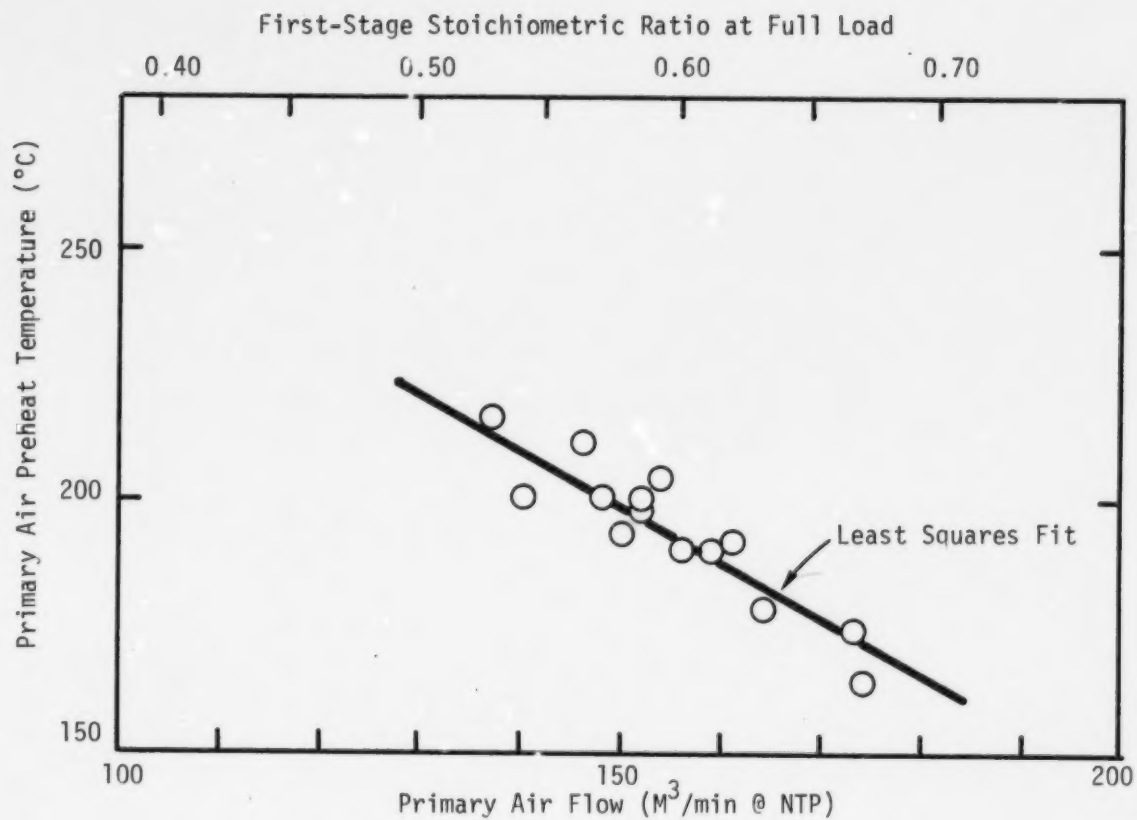


Figure 4-14. Primary air preheat temperature (before entering air register) as a function of primary air flow for full-load condition.

At the conclusion of the tests the lining was inspected for mechanical damage. Overall appearance of the lining was very good. The primary observations were:

- Cracks had formed at some of the mortared joints between bricks.
- Inspection of axial expansion joints suggest some permanent movement of the lining or shell had occurred.
- Minor to moderate cracking and surface spalling had occurred in the plastic refractory at the first-stage exit.

The cracks at mortared brick joints were minor, except for a moderate crack in the front wall extending radially from the primary throat to the outer diameter of the wall. The appearance and location of the crack suggest that it was formed during the burner cool-down. The refractory manufacturer was consulted and in their estimation the crack posed no danger to the lining integrity and corrective action was limited to packing the crack with ceramic fiber. Other cracks were judged to be minor and no corrective action was recommended.

The refractory lining was constructed with three 2.5 cm-wide (7.5 cm total expansion allowance) axial expansion joints to allow for thermal expansion of the brick at full temperature. After the test total joint width was 3.4 cm. A large gap in the brick, approximately 4.5 cm wide, had also appeared at the junction between the primary air and secondary air shells (see Figure 4-15). This suggests that the rear part of the lining may have shifted toward the front of the burner, as illustrated in Figure 4-15. This may have resulted in a gap between the brick and inner shell at the conical section of the lining. The refractory installer believes that since the cone is arch-supported this poses no clear threat to lining integrity. However, since only about 60 percent of the total expansion predicted seems to have occurred, it was decided to fill one of the expansion joints with plastic refractory to prevent further movement of the cone. The remaining gaps will be repacked with ceramic fiber prior to the next firing.

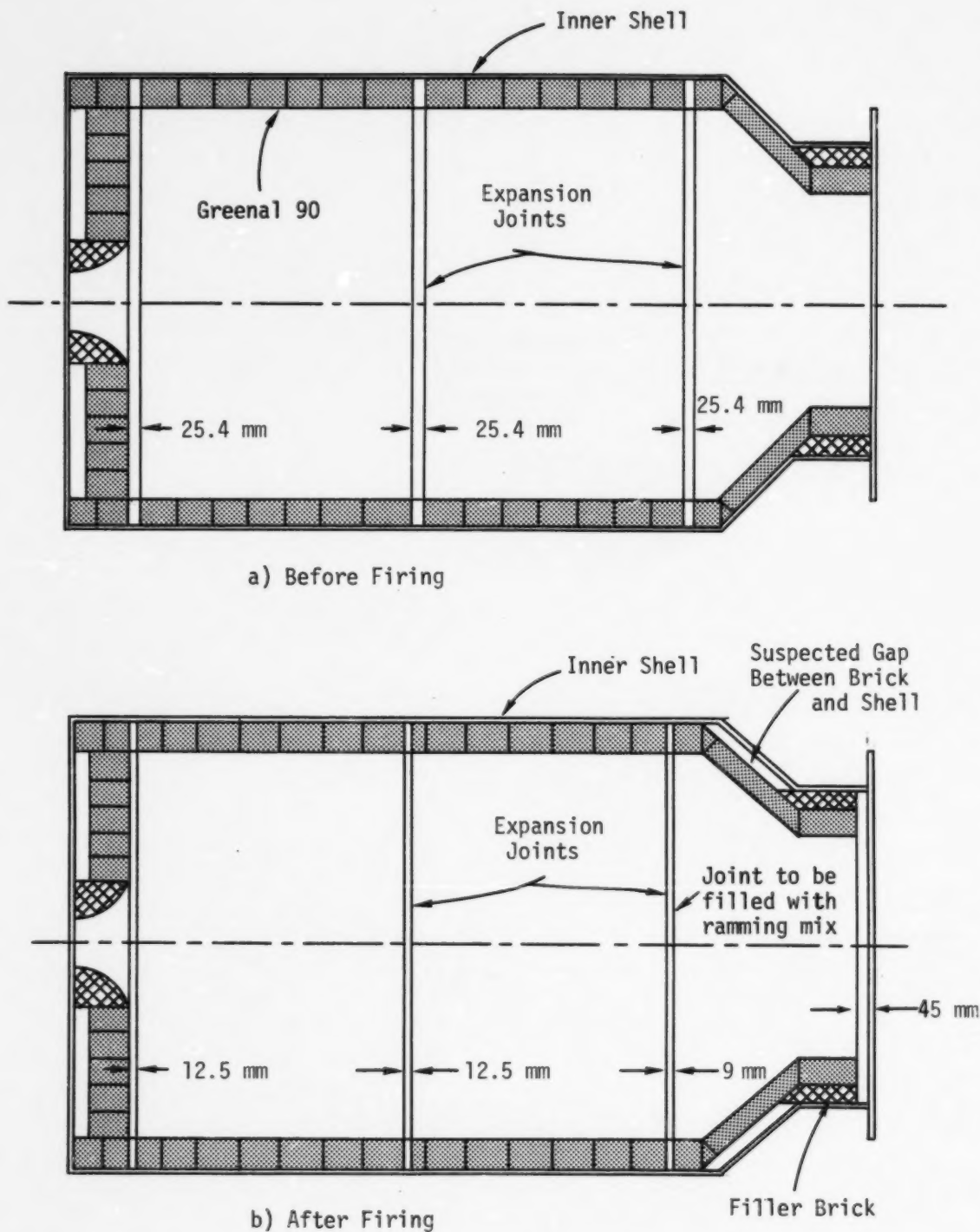


Figure 4-15. Refractory lining before and after firing.
(Note: Not to scale)

The plastic ramming mix (Greenpak-90tm) which was used to form the burner exit and radial secondary air ports, appears to be intact and in no danger of failure. Several cracks appeared through the lining, particularly near the radial air ports, and some surface bubbles were present. The refractory installer indicated that since the material is anchored to the shell there was no danger of failure, and no corrective action was recommended.

4.2.2 Control System

The control system consists of control valves, actuators, flow and temperature instrumentation, logic relays and solenoids, a flame safety relay, and a programmable controller. The functions of the control system are to:

- provide safe start-up and shut-down;
- regulate full flow based on steam demand;
- trim air flow to maintain first-stage stoichiometry and overall excess oxygen for minimum pollutant emissions;
- provide emergency action in the event of high shell temperatures.

The final control approach which was adapted for the prototype burner is outlined in Figure 4-16. The burner control system utilizes pneumatic parallel positioning control strategy where the final control elements (i.e., fuel control valve, primary air damper and secondary air damper) are operated based on the steam generator's existing feedwater flow rate signal. The first-stage air flow and the flue gas oxygen are maintained at optimum settings using electronic signals to bias the pneumatic signals. These electronic signals are generated by a programmable controller which utilizes fuel flow and first-stage air flow measurements to generate a bias signal to the primary damper actuator, and a flue gas oxygen sensor is used to produce a second bias signal to the secondary air damper actuator.

The programmable controller output is converted to a pneumatic signal by a current/pneumatic (I/P) converter. This pneumatic signal is added to the feedwater flow signal which goes to the primary or secondary air damper actuator. The pneumatic signal is limited in range to prevent an upset

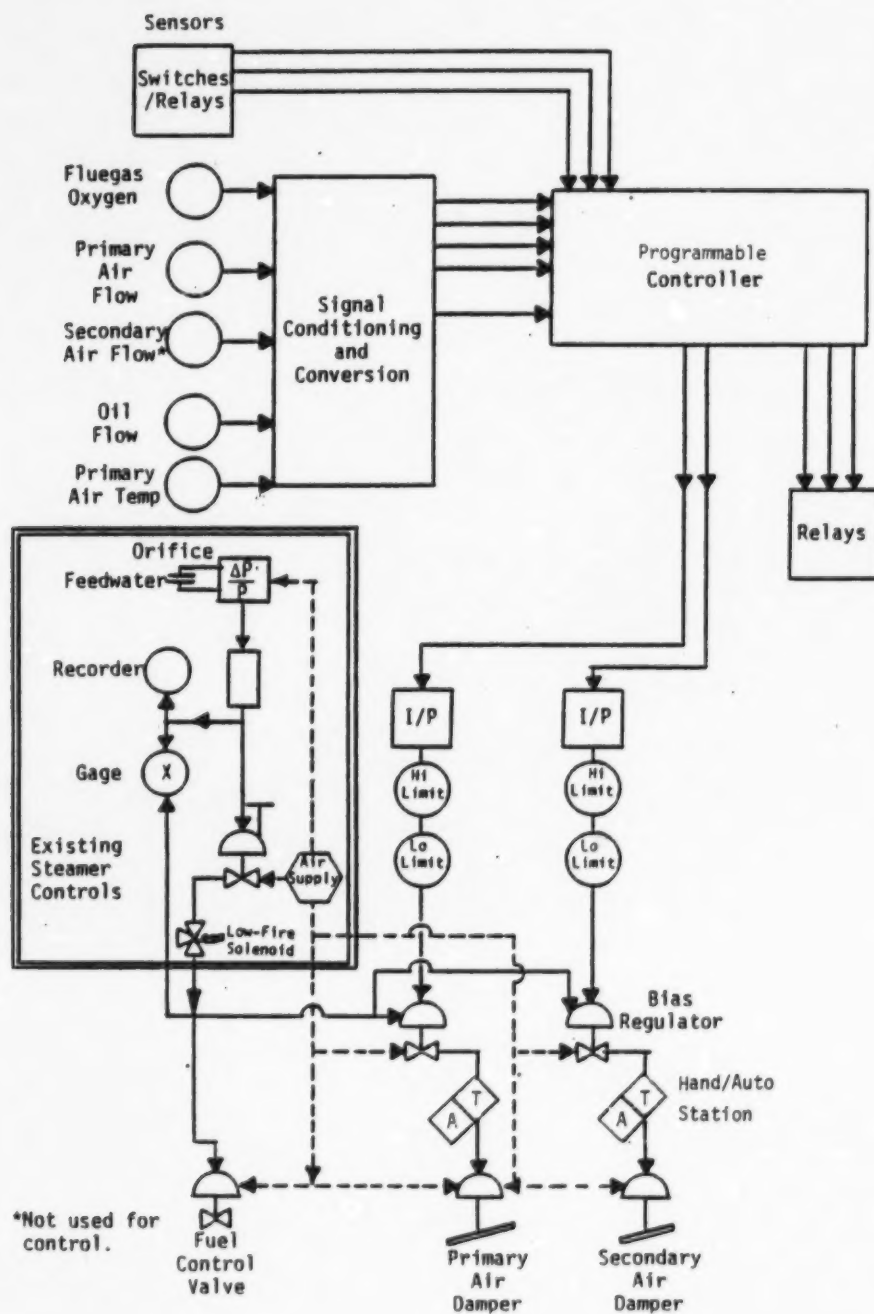


Figure 4-16. Hybrid pneumatic/electronic control system.

should the electronic signal fail. The pneumatic system is designed to maintain the burner within 10 percent of optimum in the event of electronic failure.

In addition to the trim controls for emission optimization the burner control system also incorporates logic relays for start-up and shut-down sequences. These controls are designed to provide safety sequences in the event of a power failure, loss of combustion air or high shell temperature. The relay logic was designed to easily interface with the host steam generator for the field demonstration.

The remainder of this subsection will describe the operation of the control system in terms of:

- Ignition and Shut-Down Sequences
- Pneumatic Controls
- Automatic Trim Controls

The ignition and shut-down sequences are governed by a series of timers, logic relays, limit switches and a commercial flame safeguard controller (by Fireye Corporation). The ignition sequence consists of a pre-purge cycle, safety limits check, and a pilot ignition cycle (including a check for pilot flame). If the pilot flame is detected, then the main fuel valve is energized. If the pilot flame is not detected by the end of a timed interval, the pilot gas valve and igniter are de-energized and a post-purge cycle is initiated for another timed interval. Tests were carried out to check the start-up and shut-down sequences. Both normal and emergency sequences (e.g., steel shell overheat or low draft) were tested. Flame discrimination tests were also conducted to verify that the U.V. flame detector does not respond to the hot refractory wall. Test results indicate that all sequences including all the built-in safety limits operated as designed. All other control systems components such as solenoid valves, actuators, transducers, transmitters, logic relays, etc. performed satisfactorily.

The burner control system was designed to provide final control over the fuel valve, the primary air damper and the secondary air damper, in addition to the sequences just discussed. The two air dampers can be operated independently either in manual mode or automatic mode through a hand/auto transfer

station. When the hand/auto stations are placed in the automatic mode the air dampers are operated according to the control signal from the feedwater flow meter. The feedwater flow signal is transmitted directly to the air damper actuators when the automatic trim loop is not engaged. The trim loop can be engaged from the control panel, which will cause the programmable controller to bias the feedwater flow signal to the dampers to maintain optimum conditions. Fuel flow is not biased by the controller in order to preserve safety features built into the steam generator which keep it from being overfired.

The programmable controller converts the original positioning control strategy to a metering control strategy. To optimize the primary air flow with respect to load, the controller senses the fuel flow and the primary air flow. The controller then calculated the optimum primary stoichiometric air needed for the current fuel flow based on previous characterization of emissions. This value is then compared to the measured primary air flow from which an error value is generated. If the error exceeds a predetermined tolerance, the controller will issue a corrective signal to bias the pneumatic signal given by the feedwater flow rate.

The flue gas oxygen control loop works similarly. Oxygen concentration is measured by a commercial oxygen probe. The probe senses a signal to the controller which compares the value to a setpoint. The output signal is generated proportional to the magnitude of the error. The extent to which the controller can bias the secondary air signal is limited to prevent dangerous or smokey conditions.

Another safeguard to prevent the trim controller from producing dangerous or smokey conditions limits its operation to 80 to 100 percent of full load. This prevents the oxygen trim loop, which has a long response time due to the oxygen sensor, from over-correcting during load swings.

Manual operation was applied for the emissions optimization tests. Each of the control elements (fuel valve, air dampers) responded smoothly to changes in feedwater flow signal (simulated using a simple air regulator). Flow instrumentation also functioned satisfactorily. Aside from minor debugging normally encountered in preliminary trials, all control elements performed well.

A brief test of the primary air and oxygen trim loops was conducted. The purpose of this test was to establish response of the system to changes and establish constants (gain, lag) for the control loop. After several trials, both trim loops were demonstrated to operate satisfactorily. Final setup of the control system will necessarily take place in the field.

4.3 Ancilliary Components

The performance of other components of the burner system was generally satisfactory. The major ancilliary components are:

- blower
- oil, steam, atomizing air, and pilot gas plumbing
- primary air register

The blower operated without mishap continuously during the 160 hours encompassed in the curing and testing phases. The only blower maintenance item which required attention was adjustment of the drive belt tension.

All of the major components of the fluid plumbing performed according to design specifications. Two leaks occurred during the test. A leak in the oil line was caused as a result of a union which had come loose due to thermal cycling. Another leak occurred in the atomizing steam line due to failure of a flange gasket. All fittings were subsequently tightened and no further leaks occurred. A minor change in pilot gas plumbing will be made prior to field installation in order to increase gas flow. The atomizing steam pressure regulator will also be upgraded to prevent mixing of oil and steam in the event of diaphragm failure.

Although the primary air register is built into the primary chamber it is covered here since it was purchased from a commercial burner manufacturer. The register itself performed to design specifications. Total primary pressure drop, measured between the air flowmeter (located in the ducting from blower to shell) and the burner chamber, is shown in Figure 4-17 for the range of air flow investigated at full-load. Data is shown for two primary register settings. Pressure drop through the ducting and primary shell up to the wind-box is estimated to be 2 kPa (8 inches of water). The remaining pressure drop is taken across the register and throat. Combined pressure drop through the

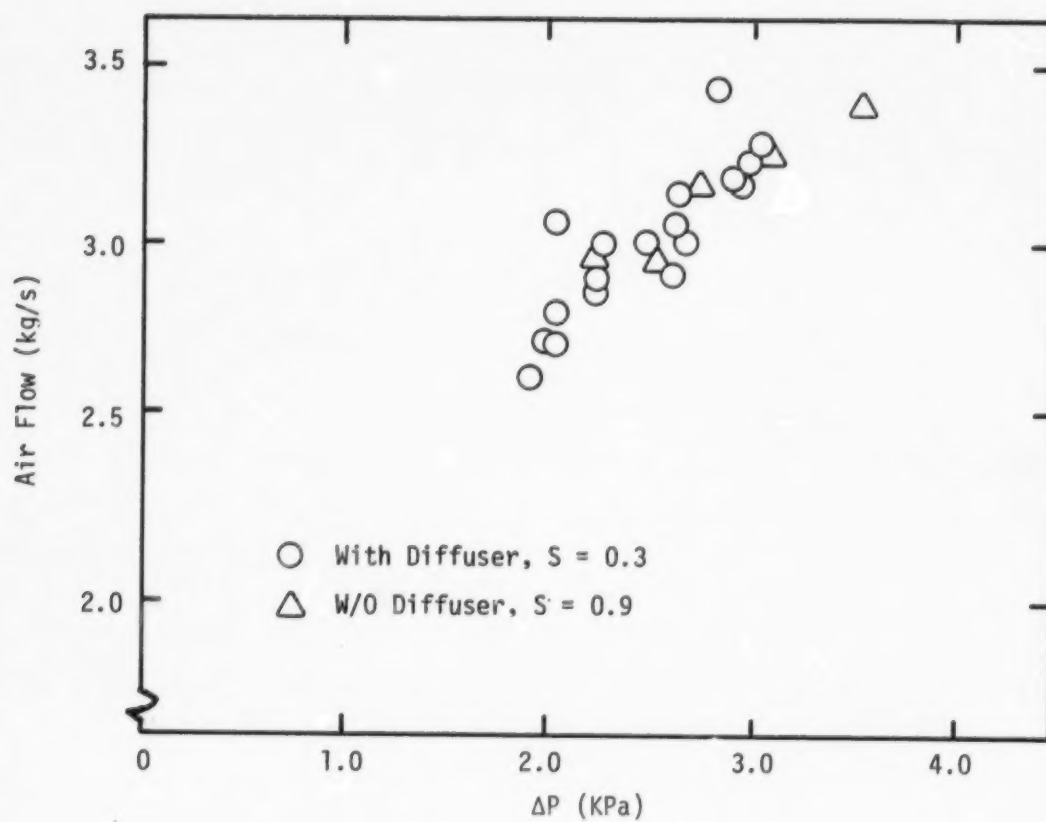


Figure 4-17. Total air pressure drop across first stage.

register and throat is high since the throat velocity is relatively high (~ 40 m/s) at the design condition, and since a very large diffuser was used. The diffuser obstructed 54 percent of the total throat area (neglecting openings in the diffuser). Velocity calculated based on the annular area surrounding the diffuser is approximately 75 m/s. During the testing the securing bolts on the diffuser came loose, the diffuser fell into the chamber and was destroyed. The register doors were closed down to produce sufficient swirl to stabilize a flame. This also produced relatively high register pressure drop.

After reviewing performance with the register manufacturer, a smaller (23 cm diameter) diffuser has been selected which should provide flame stability with lower pressure drop. Modifications will also be made to the attachment bolts to prevent them from coming loose. Because of the high pressure drop, blower speed will be increased to increase available pressure.

5.0 DISCUSSION

Burner performance was generally very close to the design performance level. NO_x emissions from the optimized burner configuration were approximately 49 ppm (corrected to 3 percent oxygen), substantially below the program goal of 85 ppm. Smoke and CO emissions were also very low under these conditions. Hardware performance appeared to be satisfactory although extended performance data is required for a full evaluation.

NO_x emissions performance was remarkably close to what would be predicted from the early development tests on the basis of first-stage residence time at high temperature. Figure 5-1 shows minimum NO_x emissions versus first-stage residence time and includes data from the 21 kW tunnel furnace, 1 MW small prototype burner, 3 MW intermediate prototype burner, and 16 MW full-scale commercial prototype burner. Each system was scaled based on criteria given in detail elsewhere (England, et al, 1983; Pershing, et al., 1981). The key scaling parameters were residence time and temperature. Additional criteria related to mixing were developed as scale increased. All of the data from the pilot-scale prototypes and full-scale prototypes show approximately linear dependence on residence time over the range shown. NO_x emissions from the tunnel furnace are higher than the larger systems; this is attributed to higher heat losses in the small-scale system and resultant lower gas temperature. The agreement over such a large range in scale ($\sim 800:1$) confirms that the key factors controlling NO_x emissions from staged combustion systems firing high nitrogen fuels are the decay of fixed nitrogen species to N_2 in the first-stage and conversion of fixed nitrogen species to NO in the second-stage. The data would suggest that a staged system of any size can be designed to produce a specified minimum level of NO_x given the design criteria on which the current burner is based.

Smoke and CO emissions under some operating conditions were high. This was generally associated with funneling of the flame into the furnace exhaust duct. Since the duct is heavily-cooled, quenching is likely and this may account for the observed emissions. In the optimum burner configuration achieved in these tests, smoke and CO emissions were very low and insensitive to first-stage stoichiometry. Flame length could be regulated by varying the secondary air injection. Additionally, flame length could be varied over a narrow range without affecting NO_x or smoke emissions. It is anticipated that

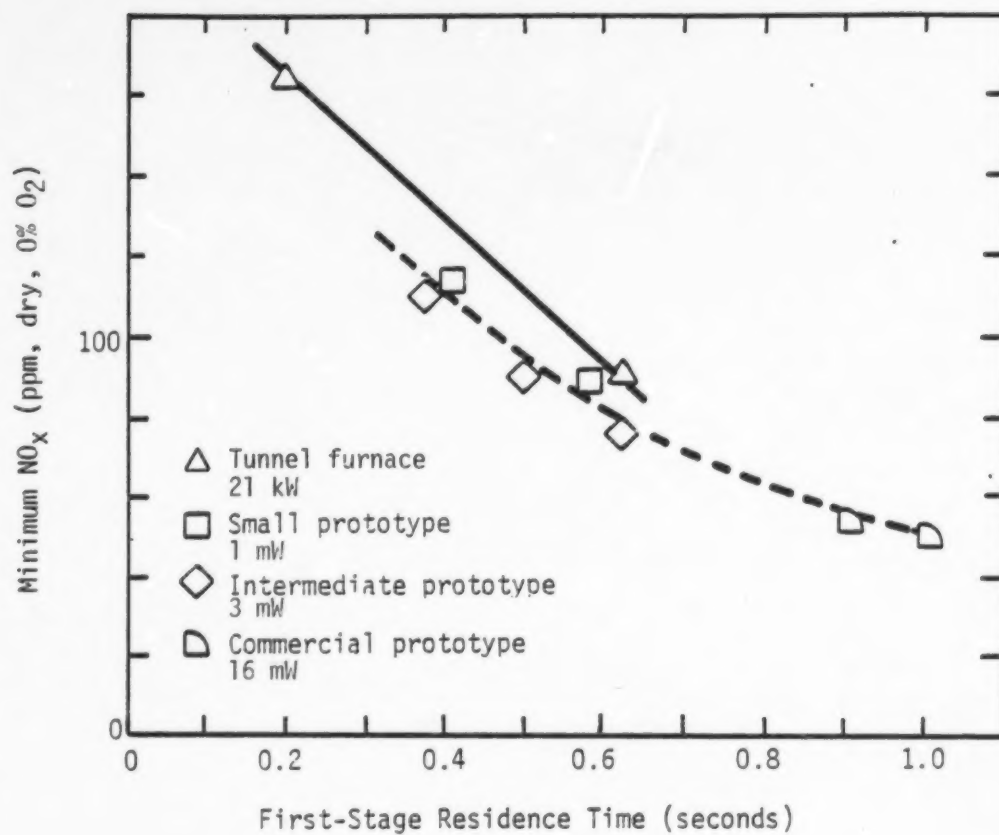


Figure 5-1. Comparison of minimum NO_x emissions from the commercial prototype burner and developmental systems.

the degree of control achieved during these tests will be sufficient for the field installation. The test tunnel has a much lower L/D than field steamers (1.5 vs 4) and 15 percent greater volume; thus, it seems likely that those flames entirely contained within the MT should easily fit into the field steamer.

In summary, the preliminary evaluation testing has demonstrated the ability of the burner to produce very low NO_x levels on a high nitrogen heavy residual oil, with low smoke and CO emissions and with a flame which appears to be compatible with field steam generators. The burner hardware has performed without serious mishap for the short duration of these tests. Final optimization and detailed evaluation of the burner hardware and control system will take place during the field evaluation.

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